DEVELOPMENT OF A FINITE ELEMENT COMPUTER MODEL OF A MOTORCYCLE USING REVERSE ENGINEERING TECHNIQUE

A Thesis

by

NATHANIEL DAVID SCHULZ

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Stefan Hurlebaus
Committee Members,	Harry Jones
	Sevan Goenezen
Head of Department,	Robin Autenrieth

August 2016

Major Subject: Civil Engineering

ABSTRACT

Over the past years, extensive research efforts have been made to improve roadside safety hardware to reduce injury to occupants of four-wheel vehicles and heavy trucks. In comparison, limited research has been conducted to address the safety of motorcycle riders when impacting roadside safety hardware. The vulnerability of motorcycle riders can lead to a high risk of injury for the rider, especially when impacting roadside barriers. In fact, motorcycle crashes were found to be the leading source of fatalities in guardrail crashes.

Physical crash testing is essential to prove crashworthiness of roadside safety barriers. No current standards exist that require upright motorcycle crash testing of motorcycles against barriers. In real-world motorcycle crashes there is a wide range of impacts against other vehicles and barriers. Reproducing these different motorcycle crash scenarios through physical crash testing can be considerably costly and time consuming. Computer simulations are a great tool to address the wide range of impacts in real-world motorcycle crashes because they are significantly less expensive and quicker than performing full scale crash tests. Motorcycle simulation models have been developed since the 1970's and have improved in complexity over the years. However, there is still a need to develop detailed motorcycle models that are geometrically accurate and can accurately predict motorcycle response behavior. This study plans to develop a finite element computer model of a motorcycle through reverse engineering that can be used to analyze impact between motorcycles and barriers.

ACKNOWLEDGEMENTS

First, I would like to thank my committee chair Dr. Stefan Hurlebaus for his guidance and support throughout my work. Also, I would like to thank my boss Dr. Chiara Silvestri Dobrovolny for her constant support and help since the beginning of my work under her. A warm thanks is extended to Robert Wunderlich and Dr. Dean Alberson for assisting with funding of this research. Without their help and support with this it would not have been possible to complete this research. A warm thanks is extended to my fellow colleagues at Texas A&M Transportation Institute Riverside for their help with my many questions and needs.

A special thanks to my wonderful wife Cassian, who has supported me and endured my many late nights of research and work. I would not have been able complete this without her amazing love and support.

Thanks be to all my friends and family who have shown great support and provided encouragement to me.

Finally, thanks be to my Lord and Savior Jesus Christ for giving me the strength and endurance to complete this research.

NOMENCLATURE

MB	Multi-rigid-Body
CAD	Computer Aided Design
FE	Finite Element
AENOR	Spanish Association for Standardization and Certification
ATD	Anthropomorphic Test Device
ISO	International Organization for Standardization
CEN	European Committee for Standardization
TC226	Technical Committee on Road Equipment
INRETS	French National Institute for Research on Transport and Safety
MPS	Motorcycle Protection System
MC	Motorcycle
OV	Opposing Vehicle
FEMA	Federal Emergency Management Agency
MADYMO	MAthematical DYnamic MOdels
CMM	Co-ordinate Measuring Machine
CNRB	Constrained Nodal Rigid Body

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Table 9. Summary of motorcycle simulation studies conducted during or after 2005. ...30

CHAPTER I

INTRODUCTION

In early motorcycle research, multi-rigid-body (MB) systems were used to model the motorcycle and rider in computer simulations. These models were advantageous due to their accuracy and quick simulation runs. However, as computational power and speeds have increased over the years, a shift has been made from multi-rigid-body modeling to finite element (FE) modeling for motorcycle computer simulations. Finite element modeling allows for increased geometrical accuracy and more accurate deformation response during impact. For the purposes of this study, LS-DYNA was used to develop the finite element model and computer simulation. LS-DYNA is a non-linear finite element analysis program and is particularly suitable for high-speed impacts.

In order to develop a detailed motorcycle model, a 3D scanner was used to scan the individual parts of the bike. Scans are then converted to Computer-Aided Design (CAD) models. This reverse engineering technique is regularly used to develop computer models of vehicles. A finite element mesh was then created for the CAD model of each part. The parts were combined to complete the finite element computer model. Computer simulations were conducted with the motorcycle impacting a rigid barrier head-on at a specified initial velocity. To validate the accuracy of the motorcycle model, measurements of the physical motorcycle, such as mass, centroid location, etc. were compared to the measurements of the motorcycle computer model. Additionally, the computer simulation robustness was determined by ensuring no numerical instability in the simulations.

The objectives of this research are the following:

- Conduct literature review to determine history of use of computer simulations to predict motorcycle and rider behavior.
- Scan and disassemble the important structural parts of the motorcycle and develop geometrical CAD models for each part.
- Develop a finite element model of the motorcycle by creating meshes for each part and assigning material and section properties.
- Validate motorcycle model by comparing mass and geometrical measurements of the physical motorcycle with computer model measurements. Ensure robustness of the computer model by running simulations with no numerical instability.
- Conduct simulation of motorcycle impacting rigid barrier at 90-degree angle.
- Compile results into final report.
- Recommend future validation work for motorcycle model.

CHAPTER II

LITERATURE REVIEW

At this time, there is no existence of an international standard procedure required to perform upright motorcycle crash testing against roadside safety devices (barriers). Worldwide, in the past decades, a few crash testing laboratories have developed their own protocols, such as L.I.E.R. in France and AENOR in Spain (L.I.E.R., 1998; AENOR, 2005; AENOR, 2008). These test procedures, however, involve impact of dummies against barriers, with the Anthropomorphic Test Device (ATD) sliding on the ground on its back. This configuration wants to represent a rider impacting a safety barrier whilst sliding on the ground, having fallen from the motorcycle. The International Organization for Standardization (ISO) developed international guidelines to cover all aspects about conducting motorcycle physical crash-testing, but this standard is referred to motorcycle impacting against a vehicle, not against a roadside barrier (ISO 13232, 2005). Moreover, since motorcycle testing is not required for federal regulation, there is not a legal requirement for crash laboratories to comply with ISO motorcycle crashing standard when developing a motorcycle crash test. The European Committee for Standardization (CEN) Technical Committee on Road Equipment (TC226) agreed on a resolution to develop a European standard for the reduction of impact severity of motorcyclist collision with safety barriers. However, even this test procedure involves impact of dummies against barriers, with the ATD sliding on the ground on its back (EN1317-8). EN1317-8 does not consider motorcycle impacts against roadside barriers while in an upright position. Moreover, it is not obligatory for any country to adopt this standard until its use is required by a national regulation.

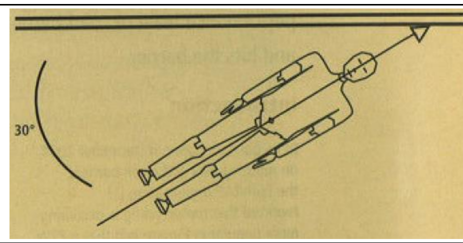
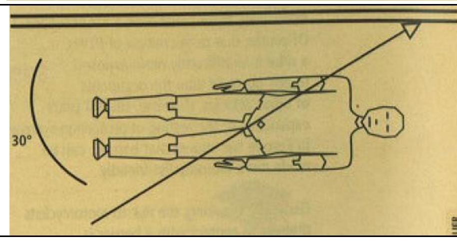
Below, motorcycle crash testing protocols are summarized. Test procedures, impact configurations, anthropomorphic test devices and severity levels are briefly explained for each protocol.

II.1 L.I.E.R. Procedure (France)

In 1998, the L.I.E.R. (Laboratoire d'essais INRETS Equipment de la Route) laboratory in France developed a dynamic test procedure for motorcyclist protection systems for safety barriers in collaboration with INRETS (the French National Institute for Research on Transport and Safety) and the French national road authority (L.I.E.R., 1998).

As described in Table 1, the L.I.E.R. procedure involves two tests and consists of launching an ATD into the protection system sliding on the ground on its back, at an impact speed of 60 km/h (37.3 mph). In the first test, the dummy is aligned with its launch path and impacts the test item head first at 30° to the test item axis. In the second test, the impact conditions remain unchanged, but the dummy is parallel to the test item. Impact point is at approximately at half-length of the system tested and opposite to a stiff element (barrier post). The complete system (safety barrier with included motorcyclist protection system) must also be subjected to full-scale vehicle crash tests according to European Standard EN 1317 part 2 (EN1317-2).

Table 1. L.I.E.R. test impact configurations (Page and Bloch, 2010).

Impact Configuration		Impact Speed	Impact Angle
Test 1. Dummy aligned w/ launch path		60 km/h (37.3 mph)	30°
Test 2. Dummy parallel to the test item		60 km/h (37.3 mph)	30°

The dummy wears standards motorcyclist clothing and a standard motorcycle helmet. The ATD used in the L.I.E.R. procedure is a standard dummy model developed for automotive crash testing applications. Several changes, however, are necessary to adapt the dummy to the impact configuration. Sensors are applied to the occipital condyles (head-neck point) of the dummy to measure head acceleration, forces and moments and compare them to several biomechanical acceptance criteria. In addition, in order to approve the system, the dummy must not pass through the system nor remain trapped in it. Since the approval of the test protocol, any motorcyclist protection systems in use on the French road network must be first successfully tested according to this procedure.

II.2 UNE-135900 Protocol (Spain)

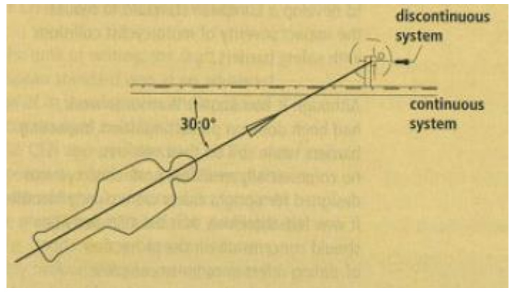
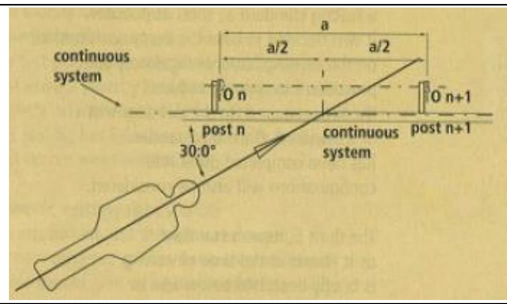
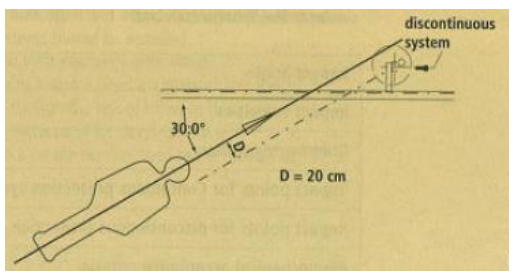
In 2003, the Spanish ministry of public works launched a research project to further develop the L.I.E.R. basic test configuration. In 2005, this study resulted in the

Spanish national standard UNE-135900 (AENOR, 2005). In 2008 a revision of the UNE-135900 standard included an additional test speed of 70 km/h (AENOR, 2008). Following are some of the main differences with respect to the L.I.E.R. protocol:

- Dummy oriented at 30° to the test item (head first) for both impacts (60 km/h);
- Second impact performed between two posts rather than opposite a post;
- Additional biomechanical acceptance criteria specified;
- Two distinct performance classes determined based on biomechanical measurements.

Discontinuous protection systems are also taken into account (protective device fitted locally around the post), which are tested with the post-centered test and with a specific head-first test with the impact point offset with respect to the post (see Table 2).

Table 2. UNE-135900 standard test impact configurations (Page and Bloch, 2010).

Impact Configuration		Impact Speed	Impact Angle
Test 1. Dummy aligned w/ launch path - Post centered		60 km/h (37.3 mph)	30°
Test 2. Dummy aligned w/ launch path - Mid-Span		60 km/h (37.3 mph)	30°
Test 3. Dummy aligned w/ the launch path - Post Offset		70 km/h (43.5 mph)	30°

II.3 EN 1317-8 Technical Specification

In 2008, the CEN Technical Committee on Road Equipment (TC226) agreed on a resolution to develop a European standard for the reduction of impact severity of motorcyclist collision with safety barriers. The proposal was to define an additional part of the EN 1317 standard, which would be primarily intended for the testing of motorcyclist protection systems to be added on to barriers. In 2009, the Spanish protocol was put forward to the TC226 to consider for adoption throughout Europe as the definitive standard EN1317-8. In 2011, the TC 226 committee decided to accept it as a Technical Specification (EN1317-8). In fact, countries with less experience with this particular type of testing felt uncomfortable with it, hence they decided to adopt it as an interim solution. Thus, it is not obligatory for any country to adopt this standard until its use is required by a national regulation. Each individual country has the option of installing barriers which they believe to be safer without subjecting them to testing, but in this case, the country or the National Road Authority, would be responsible for this decision.

At that time, no commercially available protection systems designed for upright riders were clearly identified. Therefore, the CEN decided to concentrate its activities on the protection of sliding riders in order to complete a testing standard as soon as possible, and only afterwards other rider configurations (upright position) will be considered.

The full-scale impact test consists of launching an ATD at a given speed against a barrier with Motorcycle Protection System (MPS). The ATD is sliding on its back and shall not be restrained, guided or propelled by any force external to it at the point of impact. Three approach paths are defined in Table 3. However, if the test laboratory judges that the impact point identified in this Technical Specification is not representative of the most severe testing conditions for the considered test, the point of impact can be changed accordingly. The ATD shall be aligned with the 30° approach path.

The ATD used for the tests should be a modified Hybrid III 50th percentile male ATD with following modifications:

1) Substitution of original pelvis and lumbar spine by the pelvis reference 78051-60P and the lumbar spine reference 78051-66P and their accessories to allow the ATD to adopt upright position;
2) Modification of both original shoulders to provide for the repeatable collapse during testing whereas the standard Hybrid III shoulder will exhibit unrepeatable modes of failure;
3) Installation of foam neck shield on the neck to ensure adjustment of the chin strap buckle.

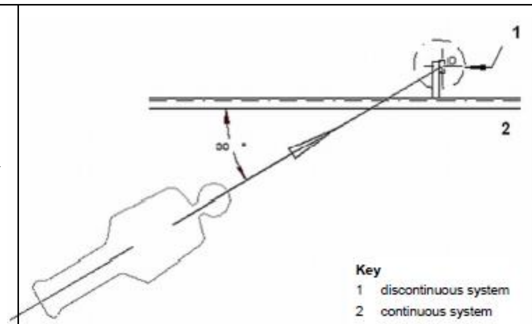
The ATD shall be equipped with a motorcycle helmet with polycarbonate shell, complying with the requirements set out in Regulation 22 of ECE/TRANS/505. The ATD should wear long-sleeved cotton tee-shirt, a leather, one-piece motorcycle suit conforming to EN 1621-1, leather gloves, and leather boots. The total test ATD mass, including instrumentation, helmet and clothing, shall be 87.5 ± 2.5 kg (193 ± 5.5 lbs). The performance of the MPS is determined by two performance classes:

- **the speed class**, determined by the impact speed of the tests;
- **the severity level**, determined by the level of the biomechanical indices obtained from the ATD instrumentation during the test (Tables 4 and 5).

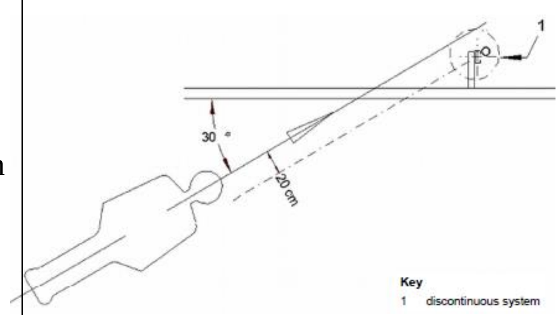
All necessary measurements to evaluate the biomechanical indices shall be carried out with measurement systems compliant with ISO 6487. The acceptance criteria of the impact test are the following:

- **MPS:** there shall be no complete rupture of any longitudinal element of the test item.
- **ATD:** the ATD shall not remain trapped in the test item. No limb, or part of a limb, nor the head or neck of the ATD shall become totally detached from the ATD following impact (except for the detachment of the upper extremity due to rupture of the frangible screws in the shoulder assembly) (Table 6).

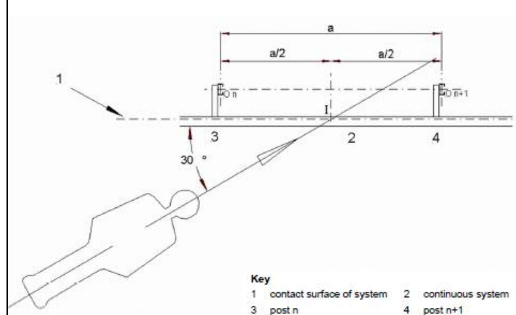
Table 3. EN1317-8 technical specification test impact configurations (EN1317-8).

<table>
<tr><th colspan="2">Impact Configuration</th><th>Impact Speed</th><th>Impact Angle</th></tr>
<tr><td>Test 1.
Launch Configuration 1: Post-Centered Impact</td><td>
</td><td>60 km/h (37.3 mph)

or

70 km/h (43.5 mph)</td><td>30°</td></tr>
<tr><td>Test 2.
Launch Configuration 2: Post-Offset Impact</td><td>
</td><td>60 km/h (37.3 mph)

or

70 km/h (43.5 mph)</td><td>30°</td></tr>
<tr><td>Test 3.
Launch Configuration 3: Mid-Span Impact</td><td>
</td><td>60 km/h (37.3 mph)

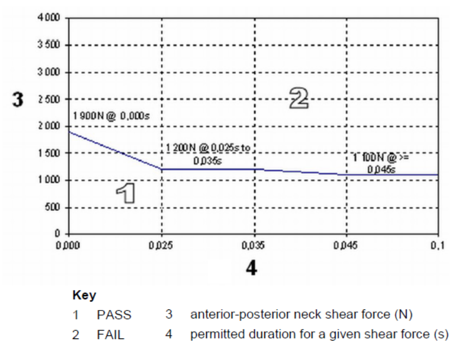
or

70 km/h (43.5 mph)</td><td>30°</td></tr>
</table>

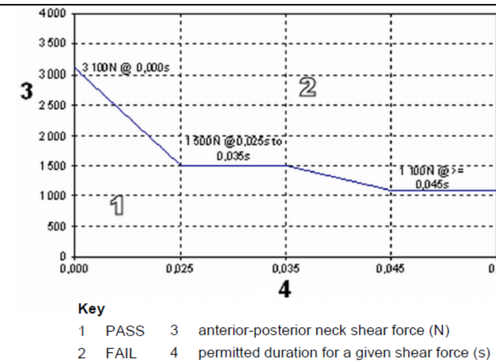
Table 4. EN1317-8 technical specification severity levels (EN1317-8).

Severity Level	Maximum Admissible Values						
	Head	Neck					
		F_x (N)	$F_{z\ ten}$ (N)	$F_{z\ comp}$ (N)	M_{OCx} (Nm)	$M_{OCy\ ext}$ (Nm)	$M_{OCy\ flex}$ (Nm)
	HIC_{36}						
I	**650**	**Table 1.5(a)**	**Table 1.5(b)**	**Table 1.5(c)**	**134**	**42**	**190**
II	**1,000**	**Table 1.5(d)**	**Table 1.5(e)**	**Table 1.5(f)**	**134**	**57**	**190**

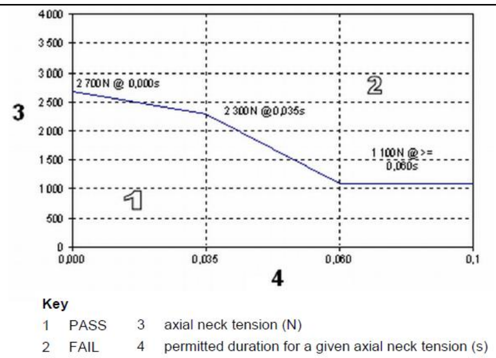
Table 5. EN1317-8 technical specification force and moment criteria (EN1317-8).



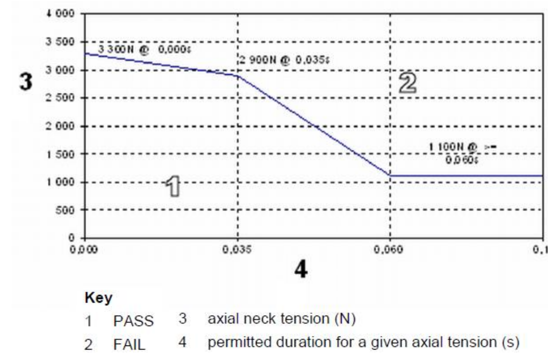
(a) Anterior-posterior Neck Shear Force Criterion for Level I



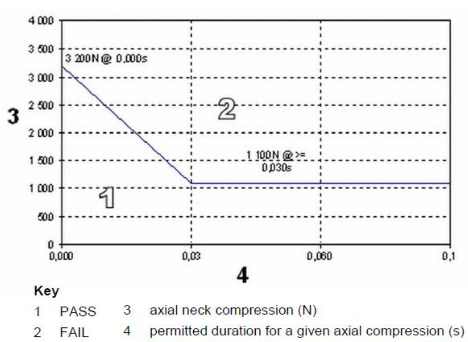
(d) Anterior-posterior Neck Shear Force Criterion for Level II



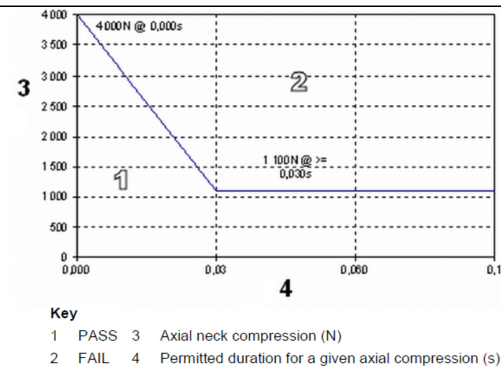
(b) Axial Neck Tension Criterion for Level I



(e) Axial Neck Tension Criterion for Level II

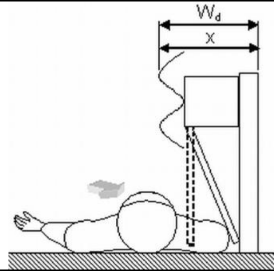
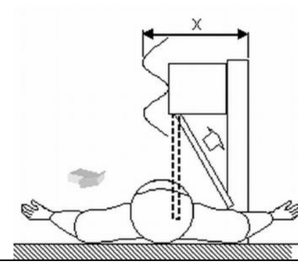
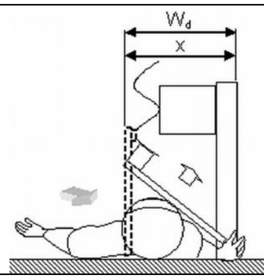
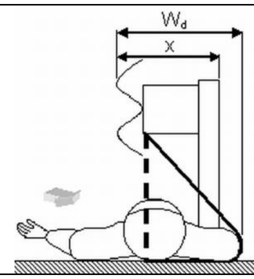
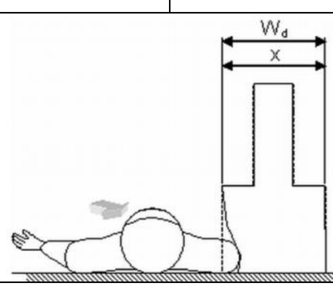


(c) Axial Neck Compression Criterion for Level I



(f) Axial Neck Compression Criterion for Level II

Table 6. EN1317-8 technical specification: determination of W_d (EN1317-8).

<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>(a) Example: barrier + MPS
No protrusions rearward of complete system</td><td>(b) Example: barrier + MPS
Arm protrudes rearward of complete system</td></tr>
<tr><td>ACCEPTABLE PERFORMANCE</td><td>SYSTEM FAILS TEST</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>(c) Example: barrier + MPS
Hand protrudes rearward of complete system but is not trapped in system after test</td><td>(d) Example: barrier + flexible MPS
ATD contained by MPS and MPS protrudes behind barrier</td></tr>
<tr><td>ACCEPTABLE PERFORMANCE</td><td>ACCEPTABLE PERFORMANCE</td></tr>
<tr><td>W_d determined by rearmost part of system</td><td>W_d determined by rearmost part of deformed MPS</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td colspan="2">(e) Integrated MPS or MPS on modular or wall-type barrier
No protrusions rearward of complete system</td></tr>
<tr><td colspan="2">ACCEPTABLE PERFORMANCE</td></tr>
<tr><td colspan="2">W_d determined by rearmost part of system</td></tr>
</table>

*W_d = Dummy Working Width

II.4 ISO 13232 International Standards

In 1996, ISO appointed a group of motorcyclist safety experts for the development of guidelines to cover all aspects of the conduct of physical crash-testing of a motorcycle impacting against a vehicle (ISO 13232, 1996). ISO 13232 consists of eight parts, under the general title "Motorcycles - Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices Fitted to Motorcycles":

- Part 1: Definitions, symbols and general considerations
- Part 2: Definition of impact conditions in relation to accident data
- Part 3: Motorcyclist anthropometric impact dummy
- Part 4: Variables to be measured, instrumentation and measurement procedures
- Part 5: Injury indices and risk/benefit analysis
- Part 6: Full-scale impact test procedures
- Part 7: Standardized procedures for performing computer simulations of motorcycle impact tests
- Part 8: Documentation and reports

Because motorcycle testing is not required for federal regulation, there is not a legal requirement for crash laboratories to comply with ISO motorcycle crashing standard when developing a motorcycle crash test.

ISO 13232-2 requires seven impact configurations between the motorcycle (MC) and the opposing vehicle (OV), which are illustrated in Figure 1 and summarized in Table 7.

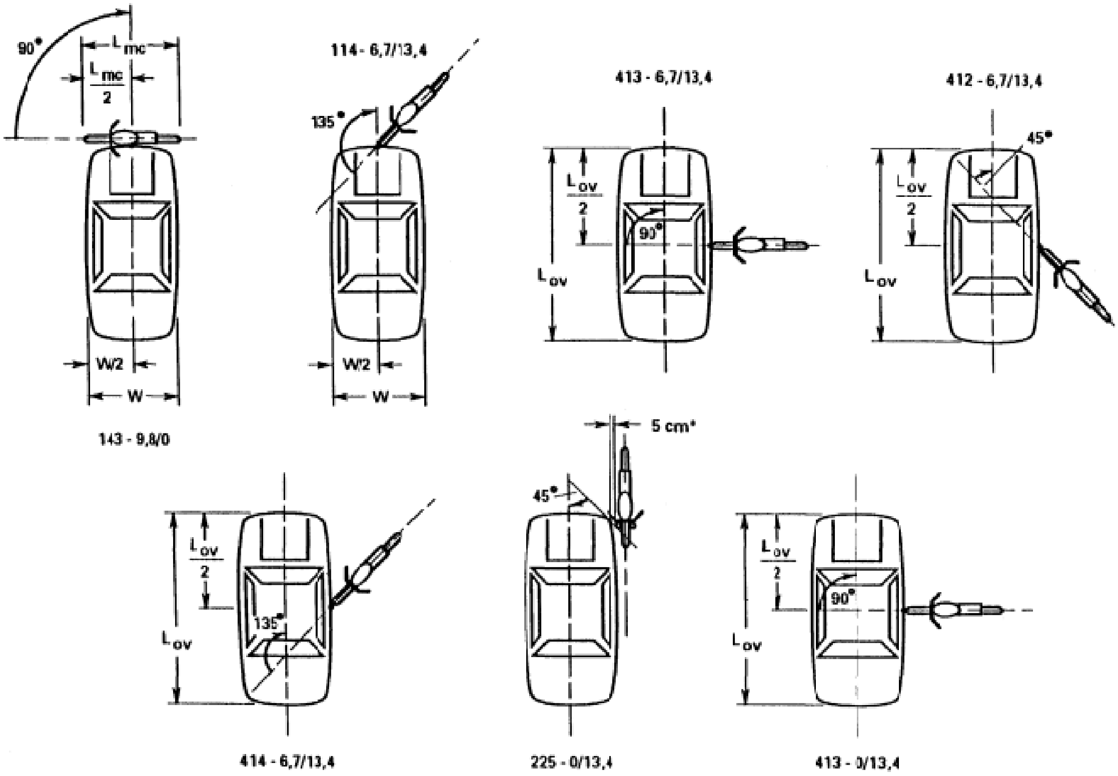


Figure 1. Different impact configurations between MC and OV (Rogers and Zellner, 1998).

Table 7. OV contact point relative tolerances for the seven required impact configurations described in ISO 13232-2 (ISO 13232, 1996).

OV contact location	Relative heading angle (deg)	OV/MC speeds (m/s)	OV/MC speeds (mph)
Front	90	9.8 / 0	22 / 0
Front	135	6.7 / 13.4	15 / 30
Front Corner	***180***	***0 / 13.4***	***0 / 30***
Side	***90***	***0 / 13.4***	***0 / 30***
Side	135	6.7 / 13.4	15 / 30
Side	90	6.7 / 13.4	15 / 30
Side	45	6.7 / 13.4	15 / 30

The basis dummy recommended by the ISO for motorcycle crash-testing is a Hybrid III 50th percentile male dummy. The ATD needs to have sit/stand construction, standard non-sliding knees and head/neck assembly compatible with either a 3- or a 6-axis upper neck load cell. In addition, certain modifications are required, and those include a sit/stand pelvis, modified elbow bushing, frangible upper-leg components and leg retaining cables (Zellner et al., 1996).

II.5 BASt Homologation Procedure

In Germany, BASt has defined a homologation procedure for impact protector (FEMA, 2010). The procedure evaluate the deceleration against the barrier protector during impact, which should not exceed 60 g as peak value, and 40 g over a 3ms interval. The report states there are two classes of devices: Class 1 which is tested with impact speed of 20 km/h (12.4 mph) and Class 2 which is tested with 35 km/h (21.7 mph). No more details regarding the two classes of devices or in general the method procedures are reported.

II.6 Motorcycle Computer Simulation Models

Since the 1970's several studies have been conducted to model motorcycle crash impacts with barriers and vehicles. As the years have progressed the models have developed in complexity and accuracy in predicting motorcycle response behavior. These computer models have been developed through multi-rigid-body (MB) or finite element (FE) methods to predict motorcycle and rider behavior during impact. Additionally, the advances in modeling software and computational speeds have allowed more complex and detailed models to be developed.

ISO 13232 was developed in 1996 and later updated in 2005 to provide common minimum requirements for research into the feasibility of protective devices fitted to motorcycles (ISO 13232, 2005). Although it has not been approved as a safety standard or law it has provided a method of evaluation necessary to be accepted by the scientific community. Specifically, Part 7 of ISO 13232, "Standardized procedures for performing computer simulations of motorcycle impact test" provides requirements for performing computer simulations and conventions for calibrating important structural features of the model. Additionally, guidelines are defined for use of computer simulations, which can be validated against data of full-scale tests.

In 2005, an extensive literature review was conducted by Rogers et al. (2005) to assess the history and current status of motorcyclist injury prediction by means of computer simulation. The results of the literature review are briefly summarized below. The summary focuses specifically on details of the motorcycle model and not rider or barrier models.

Bothwell and Petersen (1971) and Knight and Petersen (1971) developed a two-dimensional MB with a single mass motorcycle model that was used to impact a barrier. Bothwell et al. (1973), Knight and Petersen (1973) and Knight and Petersen (1976) later developed a three-dimensional MB with a four mass motorcycle model. Chinn and Hope (1987), Happian-Smith et al. (1987), Chinn et al. (1989) and Happian-Smith and Chinn (1990) describe a two-dimensional lumped mass model of a motorcycle to study motorcycle rider safety. Nieboer et al. (1993), Chinn et al. (1996) and Deguchi (2003) developed MB models of a motorcycle using MAthematical DYnamic MOdels

(MADYMO) to analyze the impact of an airbag to the rider.   Yettram (1994) and Wang and Sakurai (1999) further developed three-dimensional MB models of a motorcycle using MADYMO. Zellner et al. (1994) describes a three-dimensional MB model based used for 163 impact configurations. Rogers et al. (1994) further developed this motorcycle model to include a control volume airbag. Kebschul et al. (1998) describes one of the most complete studies conducted according to ISO 13232 standards. Full component testing was conducted along with full-scale crash testing for the different impact configurations. Iijima et al. (1998) developed a 7 mass MB motorcycle model. Canaple (2002) describes a MB motorcycle model using MADYMO. Simulations were conducted to generate head acceleration time histories that were later input into a FE model of a human head.

Chawla et al. (2001) reports one of the first complete FE models of the motorcycle. This model was further developed and used to predict rider injury according to ISO 13232 by Mukherjee et al. (2001), Nakatani et al. (2001), Mukherjee et al. (2001) and Chawla et al. (2003). Namiki et al. (2003) describes a FE model of a motorcycle using LS-DYNA. The model comprised of a 35,000 element motorcycle and 5,000 element airbag. Component testing was conducted under ISO 13232 and full-scale crash tests were performed to validate the motorcycle model.

Table 8 summarizes the reported studies by comparing motorcycle model type, motorcycle model development method, and whether or not the model was validated.

Table 8. Summary of motorcycle simulation studies performed before 2005.

Paper Title	Authors	Year	Location	Institution	Motorcycle Model Type	Model Development Method	Model Validated?
Dynamics of Motorcycle Impact, Vol I	Bothwell P W, Petersen H C	1971	U.S.	Denver Research Institute	2D multi-rigid-body model (1 rigid body)	Not stated	No
Dynamics of Motorcycle Impact, Vol III	Knight R E, Petersen H C	1971	U.S.	Denver Research Institute	2D multi-rigid-body model (1 rigid body)	Not stated	No
Dynamics of Motorcycle Impact, Vol I	Bothwell P W, Knight R E, Petersen H C	1973	U.S.	Denver Research Institute	3D multi-body motorcycle model (4 rigid bodies)	Not stated	No
Dynamics of Motorcycle Impact, Vol III	Knight R E, Petersen H C	1973	U.S.	Denver Research Institute	3D multi-body motorcycle model (4 rigid bodies)	Not stated	No
Dynamics of Motorcycle Impact, Vol III	Knight R E, Petersen H C	1976	U.S.	Denver Research Institute	3D multi-body motorcycle model (4 rigid bodies)	Not stated	No
Motorcycle Impact Simulation and Practical Verification	Happian-Smith J et al.	1987	United Kingdom	Transportation and Road Research Laboratory	2D lumped mass model (3 rigid bodies)	Not stated	No

Table 8. Continued.

Paper Title	Authors	Year	Location	Institution	Motorcycle Model Type	Model Development Method	Model Validated?
Protecting Motorcyclists Legs	Chinn B P, Hope P D	1987	United Kingdom	Transportation and Road Research Laboratory	2D lumped mass model (1 rigid body)	Not stated	No
The Effect of Leg Protecting Fairings on the Overall Motion of a Motorcycle in a Glancing Impact	Chinn B P, Happian-Smith J, Macaulay M A	1989	United Kingdom	Transportation and Road Research Laboratory	2D lumped mass model (1 rigid body)	Not stated	No
Simulation of Airbag Restraint Systems in Forward Impacts of Motorcycles	Happian-Smith J, Chinn B P	1990	United Kingdom	Transportation and Road Research Laboratory	2D lumped mass model (3 rigid bodies)	Not stated	No
Motorcycle Crash Test Modelling	Nieboer J J et al.	1993	Netherlands	TNO Crash-Safety Research Centre	3D multi-rigid-body (6 bodies)	Hand measurements	Yes
Computer Simulation of Motorcycle Crash Tests	Yettram A L et al.	1994	United Kingdom	Transportation and Road Research Laboratory	3D multi-rigid-body (4 rigid bodies)	Not stated	Yes
Preliminary Research into the Feasibility of Motorcycle Airbag Systems	Zellner J W, Newman J A, Nicholas M	1994	US/Switzerland	Dynamic Research/ International Motorcycle Manufacturers Association	3D multi-rigid-body (4 rigid bodies)	Not stated	No

Table 8. Continued.

Paper Title	Authors	Year	Location	Institution	Motorcycle Model Type	Model Development Method	Model Validated?
Development and Testing of a Purpose Built Motorcycle Airbag Restraint System	Chinn B P, et al.	1996	United Kingdom	Transportation and Road Research Laboratory	3D multi-rigid-body	Not stated	Yes
Injury Risk/Benefit Analysis of Motorcyclist Protective Devices Using Computer Simulation and ISO 13232	Kebschull S K, et al.	1998	US/Switzerland	Dynamic Research/ International Motorcycle Manufacturers Association	3D multi-rigid-body (7 rigid bodies)	Hand measurements	Yes
Exploratory Study of an Airbag Concept for a Large Touring Motorcycle	Iijima S, et al.	1998	Japan	Honda R&D Co.	Finite element model	Not stated	Yes
Development and Verification of a Computer Simulation Model of Motorcycle-to-Vehicle Collisions	Wang Y, Sakurai M	1999	Japan	Japan Automobile Research Institute	3D multi-rigid-body (8 rigid bodies)	Not stated	No
A Methodology For Motorcycle-Vehicle Crash Simulation - Development of Motorcycle Computer Simulation Model	Nakatani T et al.	2001	Japan/India	Japan Automobile Research Institute/Indian Institute of Technology	Finite element model	CMM reverse engineering	No

Table 8. Continued.

Paper Title	Authors	Year	Location	Institution	Motorcycle Model Type	Model Development Method	Model Validated?
Motorcycle-Car Side Impact Simulation	Mukherjee S et al.	2001	Japan/India	Japan Automobile Research Institute/Indian Institute of Technology	Finite element model	CMM reverse engineering	Yes
Motorcycle Wall Crash Simulation and Validation	Mukherjee S et al.	2001	Japan/India	Japan Automobile Research Institute/Indian Institute of Technology	Finite element model	CMM reverse engineering	Yes
A Methodology for Car-Motorcycle Crash Simulation	Chawla A	2001	Japan/India	Japan Automobile Research Institute/Indian Institute of Technology	Finite element model	CMM reverse engineering	No
Impact Model Development for the Reconstruction of Current Motorcycle Accidents	Canaple B et al.	2002	United Kingdom	Transportation and Road Research Laboratory	3D multi-rigid-body (6 rigid bodies)	Not stated	Yes
FE Simulations of Motorcycle Car Frontal Crashes Validation and Observations	Chawla A, et al.	2003	India	Indian Institute of Technology	Finite element model	CMM reverse engineering	Yes
Modelling of a Motorcycle for Collision Simulation	Deguchi M	2003	Japan	Yamaha Motor Co.	3D multi-rigid-body (21 bodies)	Not stated	Yes

Since 2005, several other studies have been done in regards to motorcycle injury prediction through computer simulations. They are summarized below.

Ramamurthy (2007) developed computer simulations analyzing a motorcycle and rider impacting a concrete barrier under different road conditions. The motorcycle was modeled through MADYMO and consisted of 6 bodies representing the frame, seat, wheels, suspensions and handle. The required dimensions used to model the motorcycle were obtained from the Kawasaki manufacture's handbook. Figure 2 compares the physical motorcycle and MADYMO computer model of the motorcycle. The rider was modeled as a Hybrid III 50th percentile male consisting of 37 bodies. The motorcycle model was validated by impacting the vehicle into a concrete barrier at speed of 32.2 km/h (20 mph) and 90-degree impact angle. The resulting acceleration was compared to a full-scale test conducted with the same impact conditions at Monash University, Australia (Berg et al., 2005). After validation of the motorcycle, a motorcycle with a rider model was similarly validated based off experimental data. For this simulation and test the motorcycle with a rider impacted the barrier at an angle of 12-degrees and a speed of 60 km/h (37.3 mph). This full-scale test was also conducted at Monash University, Australia (Berg et al., 2005). For this configuration the rider injury criteria for the simulation was compared to the resulting injury criteria from the test. Again, the results were close and the model was validated for this impact configuration. After fully validating the motorcycle and rider model, the next stage of the research was to predict kinematics of the motorcycle and rider and head injury suffered by the rider. This was accomplished by performing a parametric study conducted at various speeds, (40 km/h, 60 km/h, 80 km/h) various impact angles (6-degree, 8-degree, 12-degree, 24-degree, 45-degree, 60-degree, 90-degree) and under normal road condition and icy road condition. In total, 42 simulations were conducted. For each simulation HIC, Neck flexion and extension and femur loads were compared to observe the effects of the different impact conditions. A design of experiments was performed to the see the effect that each factor had on HIC rider injury. Angle of collision contributed 23%, road condition contributed 0.66% and change in speed contributed 16%.

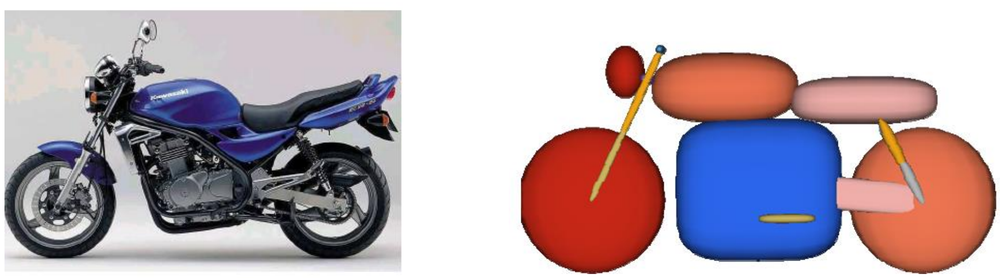


Figure 2. Comparison of physical motorcycle and computer model motorcycle (Ramamurthy, 2007).

A study was conducted by Bhosale (2013) analyzing the impact of airbags used with smaller motorcycles, which are used in India and other South Asian Countries. The aim of this study was to find appropriate triggering time for airbag inflation, backing surface, location and orientation of airbag, and size of airbag. First, the finite element motorcycle model was developed by taking a representative Indian motorcycle and measuring dimension details for individual parts and developing models of the parts using HyperMesh software. Some of the simpler parts were measured by hand, while a

Co-ordinate Measuring Machine (CMM) was used to measure dimensions of the more complex parts. Only parts that were considered important to the structural integrity of the motorcycle were modeled. This included the following parts or systems: fuel tank, rear suspension, front suspension, tire, wheel, exhaust pipe, engine and seat. Other additional parts were modeled for rider behavior such as, handlebar and foot-rest. Information such as part weight, moment of inertia, and center of gravity was also obtained. A comparison of the physical motorcycle and developed FE model of the motorcycle is shown in Figure 3. To validate this motorcycle model a rigid wall barrier test was simulated. The resulting barrier wall forces from the FE simulation were compared to the full-scale crash test. The full-scale test was conducted with a motorcycle weighing 218 kg, while the FE motorcycle weighed 100 kg. However, the magnitude of barrier forces was found to be proportionate to motorcycle weight and it was concluded that the motorcycle model could be used for further test simulations. An airbag model was developed and evaluated by performing barrier test simulations of 90 degree and 45 degree angles of impact. It was concluded that an airbag of 142L size is most promising in reducing energy of rider's head.

Figure 3. Comparison of physical motorcycle and computer model motorcycle (Bhosale, 2013).

Ibitoye et al. (2009) developed a 4 mass multi-rigid-body motorcycle to impact a finite element model of a w-beam guardrail. No mention is made of validation of the motorcycle model in the study. Using MADYMO three simulations were performed of the motorcycle crashing into the w-beam guardrail. The motorcycle was given initial speeds of 32 km/h (19.9 mph), 48 km/h (29.8 mph), and 60 km/h (37.3 mph) and an impact angle of 45 degrees. Potential injury risk was predicted for the three simulations for the following injury parameters: HIC, neck tension, neck shear, neck bending, chest acceleration and femur. For each impact speed several of the injury parameters were determined to be above the tolerance injury risk level. The re-design of guardrails is recommended to reduce severity of injury to the rider.

Chawla and Mukherjee (2007) discuss the process of developing an FE simulation that meets the requirements of ISO 13232 and evaluates airbags. The motorcycle model was developed through reverse-engineering techniques using a Co-ordinate Measuring Machine (CMM). Figure 4 shows the completed FE model. Previous studies were referenced in which the motorcycle model used was validated through a variety of impact configurations as specified by ISO 13232. Simulations were conducted by varying initial distance between dummy and the airbag. Head x and y acceleration was compared for each of the different simulations. This study was an initial report evaluating the suitability of airbags in motorcycles. The injury sustained by the rider during the airbag deployment was predicted to be a low probability and the variation of initial distance between dummy and airbag did not have a significant impact on rider injury.

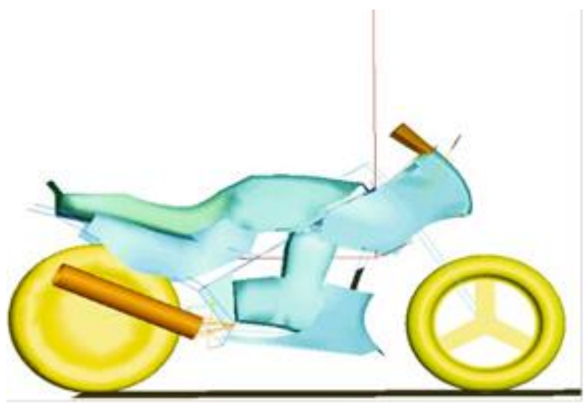


Figure 4. Finite element computer model of a motorcycle (Chawla and Mukherjee, 2007).

Namiki et al. (2005) used a previously validated computer motorcycle model (Chawla et al., 2003) to predict rider injury in 200 impact configurations and 400 cases as specified by ISO 13232. The FE model of the motorcycle is shown in Figure 5. Several full-scale tests were conducted and used to further validate the motorcycle model with an airbag. After validation of the motorcycle model, injury reduction analysis was performed according to ISO 13232. The average results of all the performed simulations showed that the airbag had a positive effect in injury reduction.

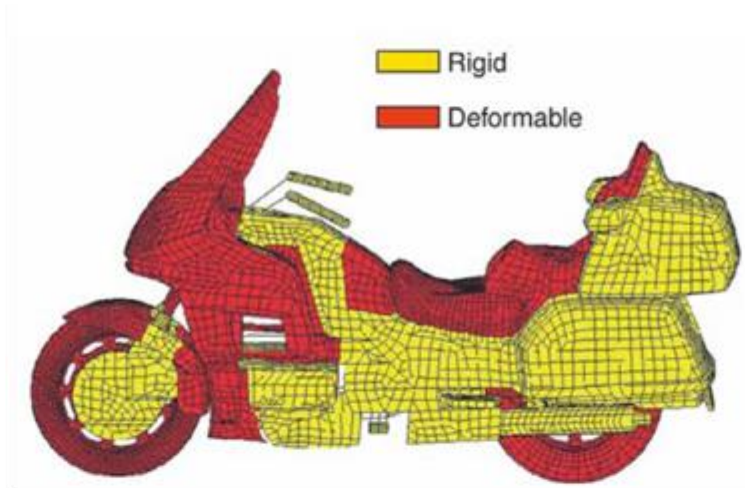


Figure 5. Finite element computer model of a motorcycle showing deformable and rigid parts (Namiki et al., 2005).

Table 9. Summary of motorcycle simulation studies conducted during or after 2005.

Paper Title	Authors	Year	Location	Institution	Motorcycle Model Type	Model Development Method	Validated Model?
A Computer Simulation For Motorcycle Rider Injury Evaluation In Collision	Namiki H, Nakamura T, Iijima S	2005	Japan	Honda R&D Co.	Finite element model	Unknown	Yes
Kinematic Analysis of a Motorcycle and Rider Impact on a Concrete Barrier Under Different Impact and Road Conditions	Ramamurthy, S	2007	US	Wichita State University	Multi-rigid-body (6 bodies)	Hand measurements	Yes
Motorcycle Safety Device Investigation A Case Study on Airbags	Chawla A, Mukherjee S	2007	India	Indian Institute of Technology	Finite element model	CMM reverse engineering	Yes
Simulation of Motorcycle Crashes with W-Beam Guardrail Injury Patterns and Analysis	Ibitoye A B, et al.	2009	Malaysia/ Qatar	Road Safety Research Centre/Qatar University	Multi-rigid-body (4 bodies)	Hand measurements	No
Exploratory Study on the Suitability of an Airbag for an Indian Motorcycle Using Finite Element Computer Simulations of Rigid Wall Barrier Tests	Bhosale, P V	2013	India	Indian Institute of Technology	Finite element model	CMM and hand measurements	Yes

CHAPTER III

MOTORCYCLE SCANNING

The methodology to reverse-engineer a motorcycle is detailed in this chapter. The motorcycle to be modelled was selected to be a 2005 Kawasaki Ninja 500R. This motorcycle was selected based on popularity among riders, dimensions, and rider posture. These are important criteria because they affect the likelihood of a rider and motorcycle being involved in a crash. The Kawasaki Ninja 500R has a smaller build and causes riders to have a forward position and lean due to the geometry of the bike and footrest locations.

III.1 Global Scan Setup

Two different scanners were used throughout the scanning process. The Surphaser® HSX laser scanner produces quick 3D scans of a selected area with an accuracy of ± 0.2 mm (0.008 in). Figure 6 shows the Surphaser placed on a tripod for stability. The Surphaser scanner is best used to scan large parts or entire vehicles from a distance of about 3 m (10 ft). The Surphaser was used to develop global scans of the entire motorcycle and to scan larger parts such as the engine, fuel tank, and frame.

Figure 6. Surphaser scanner placed on tripod.

The FARO Edge 3D laser scanner is a portable CMM that is commonly used for reverse engineering (Figure 7). The FARO scanner is ideal for scanning small parts and is accurate within ± 25 µm (0.001 in). This scanner was used to scan a majority of the individual motorcycle parts after disassembly.

Figure 7. FARO Edge 3D laser scanner.

The first step in the scanning process was to develop global scans of the entire motorcycle. This was done so that parts could later be aligned to their correct global position in reference to the entire motorcycle. The Surphaser scanner was used during this step because it can quickly scan a large area while still maintaining a good accuracy.

In order to capture a full geometrical scan of the motorcycle, it was lifted into the air and scanned. The motorcycle was steadied by placing posts for the bike to rest against. This allowed the front and rear tire to be in their proper geometrical shape while scanning. Additionally, in order for the Surphaser to accurately capture the motorcycle geometry, it was sprayed with white Magnaflux. Magnaflux creates a white coating over the parts that reduces reflectivity or "shininess" of the parts producing a better scan. Figure 8 shows the bike lifted in the air and sprayed with Magnaflux.

Figure 8. Motorcycle sprayed with Magnaflux suspended in the air.

To capture the full geometry of the motorcycle the Surphaser was placed at different locations around the motorcycle. Figure 9 shows the eight different locations that the Surphaser was placed around the motorcycle. For each scan the Surphaser was about 3 m (10 ft.) away. Figure 10 shows an example setup with the Surphaser in one of the corner locations.

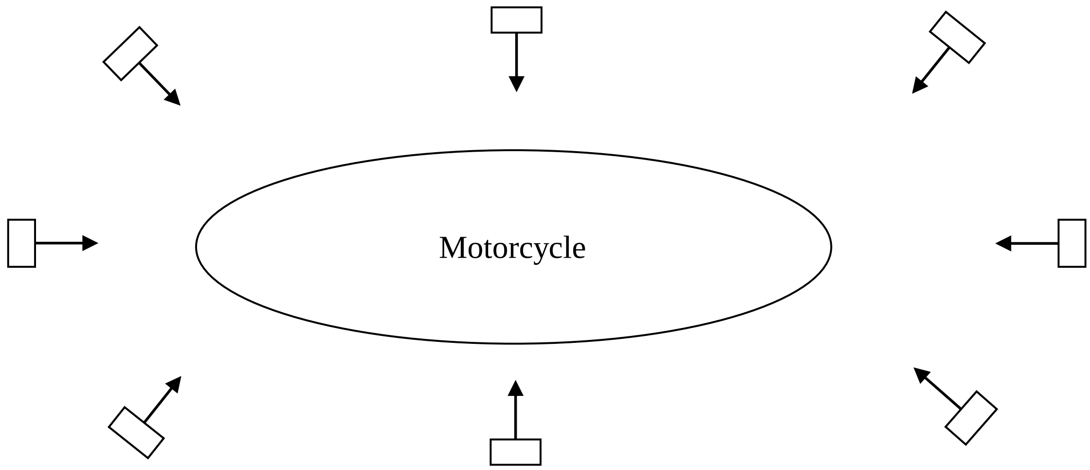


Figure 9. Placement of Surphaser scanner around motorcycle.

Figure 10. Surphaser placed in corner position to scan motorcycle.

With the motorcycle position approximately level with the laser scanner, some parts were not accurately captured. Several of the top and bottom parts of the motorcycle were not fully captured. In order to capture the geometry of the other parts two different positions of the motorcycle were specified. This included lowering the motorcycle to where it was just above the ground (Figure 11) and tilting it by raising the front portion (Figure 12). Similar to the previous motorcycle position the Surphaser scanner was placed at different locations to capture the geometry of the parts.

Figure 11. Motorcycle lowered to just above ground to scan top of motorcycle.

Figure 12. Motorcycle raised front to capture underneath portion of motorcycle.

After successfully capturing all the outer details of the motorcycle, several of the outer plastic cover parts were removed to expose the inner parts (Figure 13). Similar to the previous process with the covered motorcycle, scans were taken from several different angles and with the motorcycle in different positions to fully capture the details of the parts.

Figure 13. Motorcycle with removed outer coverings to expose inner parts.

III.2 Global Scan Process

Through the scanning setup described previously, computer scans were generated at several different angles and different motorcycle positions. A 3D scanning and reverse engineering software, Geomagic Design X, was used throughout the scanning process. Scans were taken from the Surphaser scanner and imported into Geomagic to be processed. These scans contain thousands of different points that make up the geometry of the motorcycle or more easily referred to as a point cloud. Figures 14 and

15 show examples of a Surphaser scan setup and the corresponding point cloud in Geomagic.

Figure 14. Example Surphaser scan setup and resulting point cloud from scan.

Figure 15. Second example Surphaser scan setup and resulting point cloud from scan.

Combining the scans at different angles and positions and aligning the scans resulted in a complete point cloud representation of the motorcycle (Figure 16).

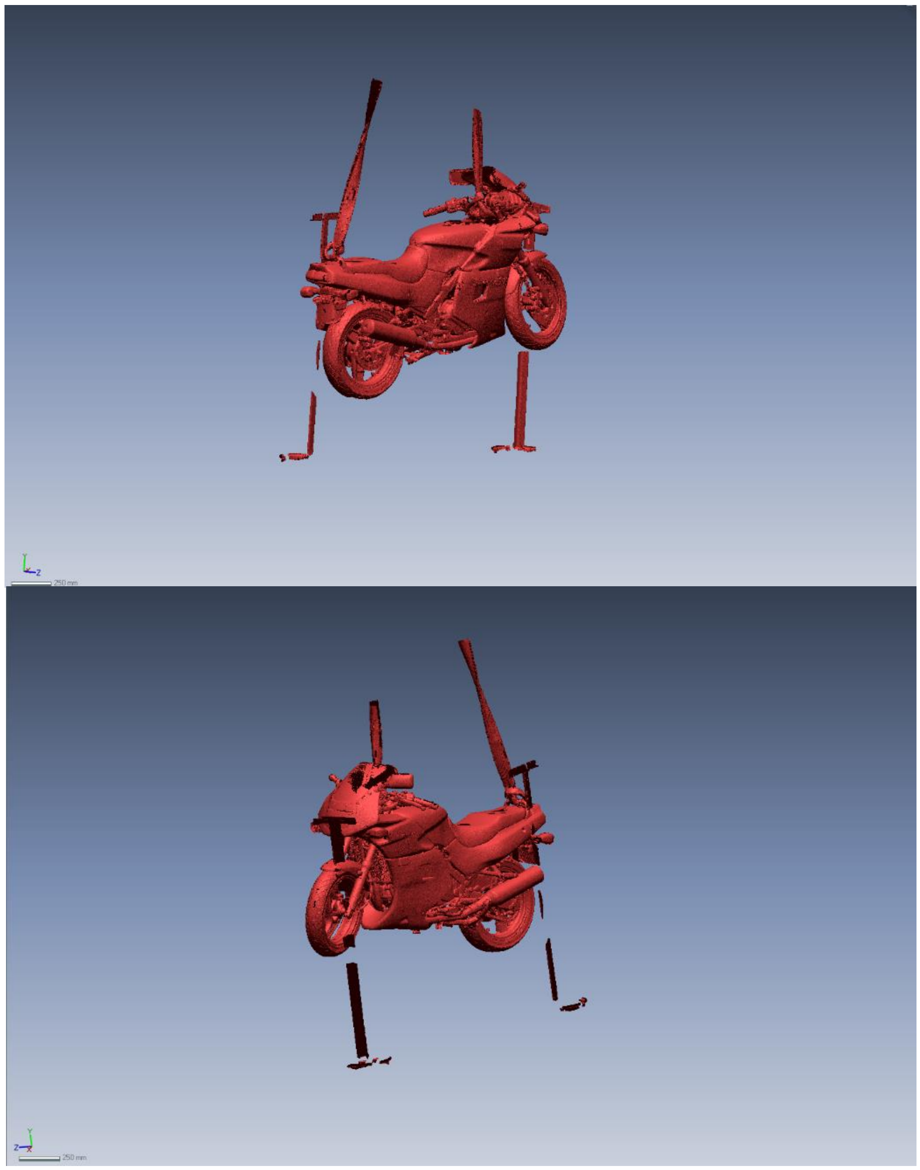


Figure 16. Complete aligned scans for covered motorcycle.

The same process was followed for the exposed motorcycle without the covered parts. Figure 17 shows the combined scans from the different angles and different positions.

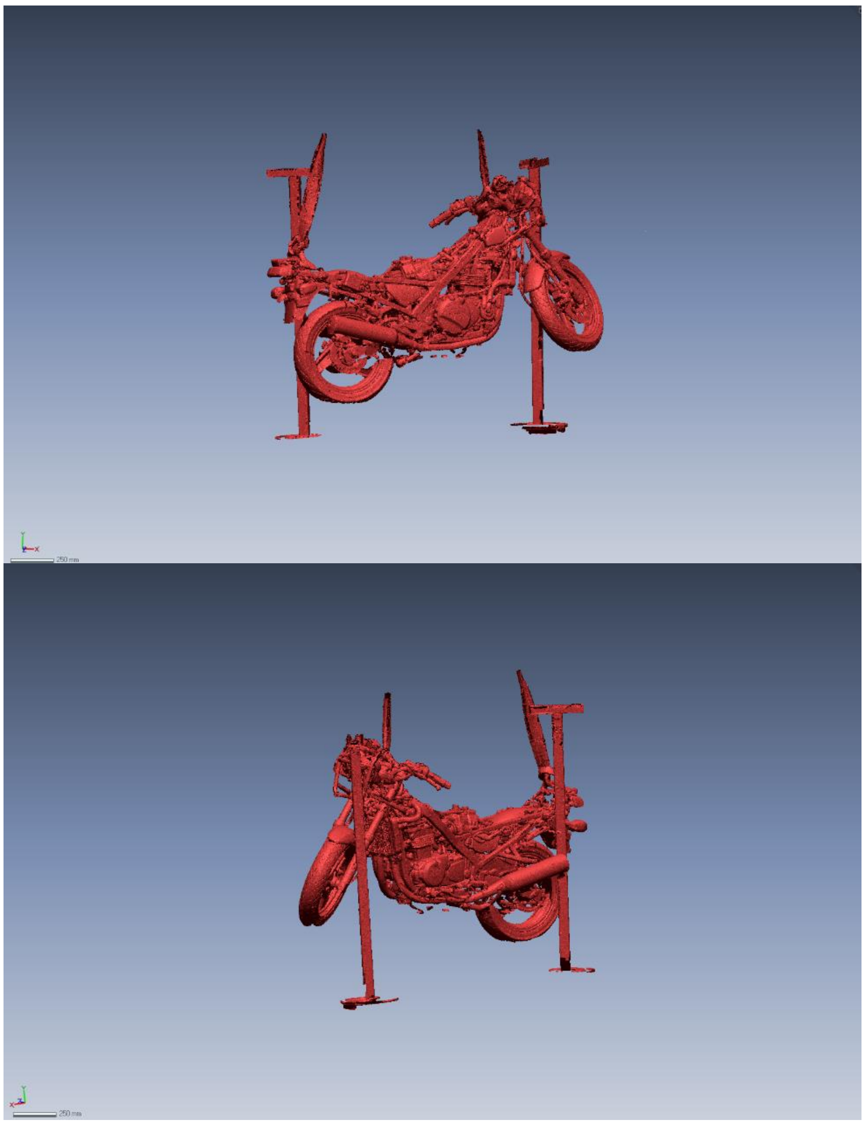


Figure 17. Complete aligned scans for exposed motorcycle.

III.3 Scanning of Individual Parts

After developing global scans and point clouds for the entire motorcycle it was necessary to develop individual scans of the structural parts and components. A catalog was found online that lists all the parts for the Kawasaki Ninja 500R motorcycle. This list was used to document all parts that needed to be scanned. The parts are listed below:

- Air Filter
- Bracket Ignition Left
- Bracket Ignition Right
- Bracket Igniter
- Brake Pedal
- Bracket Regulator
- Gear Change Pedal
- Engine
- Left Inner Cowling Cover
- Right Inner Cowling Cover
- Bracket Meter
- Right Pipe Exhaust
- Left Pipe Exhaust
- Right Muffler
- Left Muffler
- Bracket Carburetors
- Left Carburetor
- Right Carburetor
- Rear Brake Pad
- Battery
- Swing Arm
- Bracket Battery
- Chain Case
- Front Windshield
- Center Inner Cowling Cover
- Upper Cowling
- Right Mirror
- Left Mirror
- Upper Cowling Bracket
- Lower Cowling
- Left Lower Cowling Bracket
- Right Lower Cowling Bracket
- Reservoir
- Radiator
- Fan Bracket
- Fan Assembly
- Rear Brake Disc
- Shock Absorber
- Kick Stand
- Center Stand
- Kick Stand Bracket
- Front Fender
- Front Rear Fender
- Back Rear Fender
- Footrests (x4)
- Step Holder (x4)
- Rear Frame Grip
- Frame
- Front Brake Disc
- Front Brake Pad
- Left Taillight
- Right Taillight
- Front Left Fork
- Front Right Fork
- Upper Fork Holder
- Lower Fork Holder
- Rear Taillight
- Bracket Rear Taillight
- Bracket Lamp Bulb
- Front Tire
- Front Wheel
- Seat
- Seat Cover
- Fuel Tank

- Rear Fuel Tank Bracket
- Front Fuel Tank Bracket
- Left Suspension Tie Rod
- Right Suspension Tie Rod
- Suspension Arm
- Rear Tire
- Rear Wheel
- Regulator
- Right Frame Pipe
- Meter Housing
- Headlight
- Left Side Cover
- Right Side Cover
- Igniter
- Rear Caliper Holder

The methodology for developing a CAD surface or solid model for an individual part in Geomagic is documented below. The process for each part will not be detailed but the overall procedure that was followed for each individual part will be outlined. The rear frame grip was used as an example to describe the methodology (Figure 18).

Figure 18. Rear frame grip from Kawasaki Ninja 500R motorcycle.

Using the FARO scanner a point cloud was developed for the rear frame grip as seen in Figure 19.

Figure 19. Point cloud representation of rear frame grip.

After developing the point cloud for the rear frame grip it is necessary to position it in its' correct global position. This is accomplished by aligning the point cloud for the part developed by the FARO to the part in the global scan point cloud developed by the Surphaser. Figure 20 shows the complete motorcycle (green) and the aligned individual rear frame grip (red).

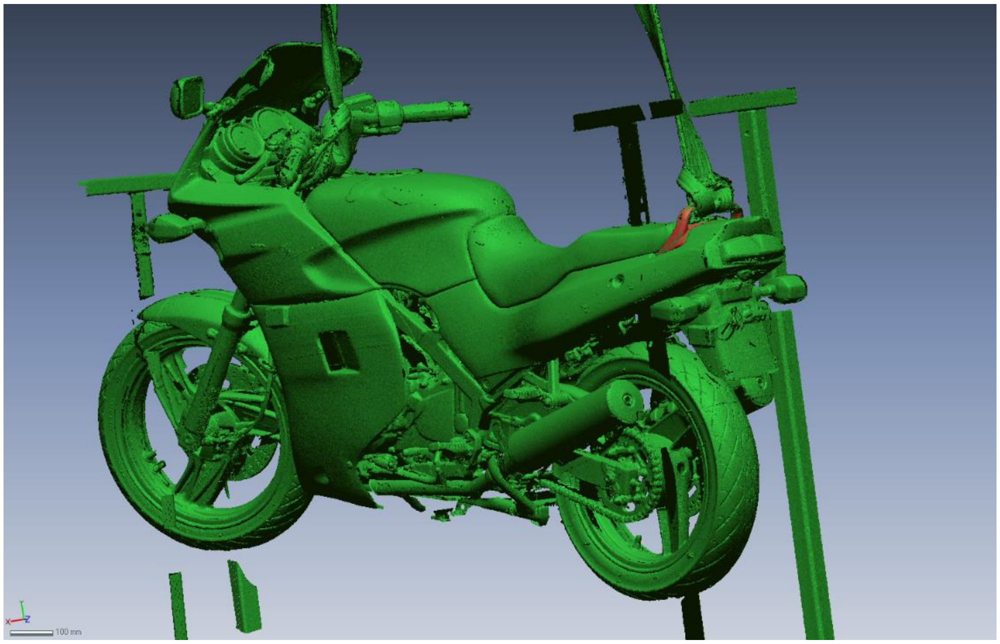


Figure 20. Aligned rear frame grip point cloud to complete motorcycle point cloud.

Next, the point cloud is developed into a mesh (Figure 21). This mesh connects all the cloud points together into small triangles forming an overall surface mesh. Figure 22 shows a close-up view of the triangles forming the mesh.

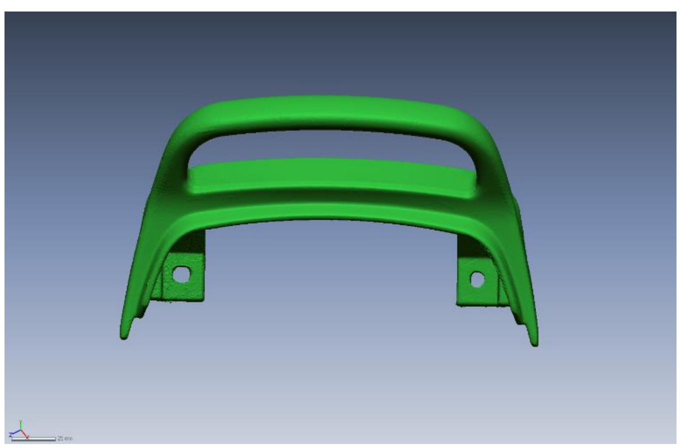


Figure 21. Geomagic mesh for rear frame grip.

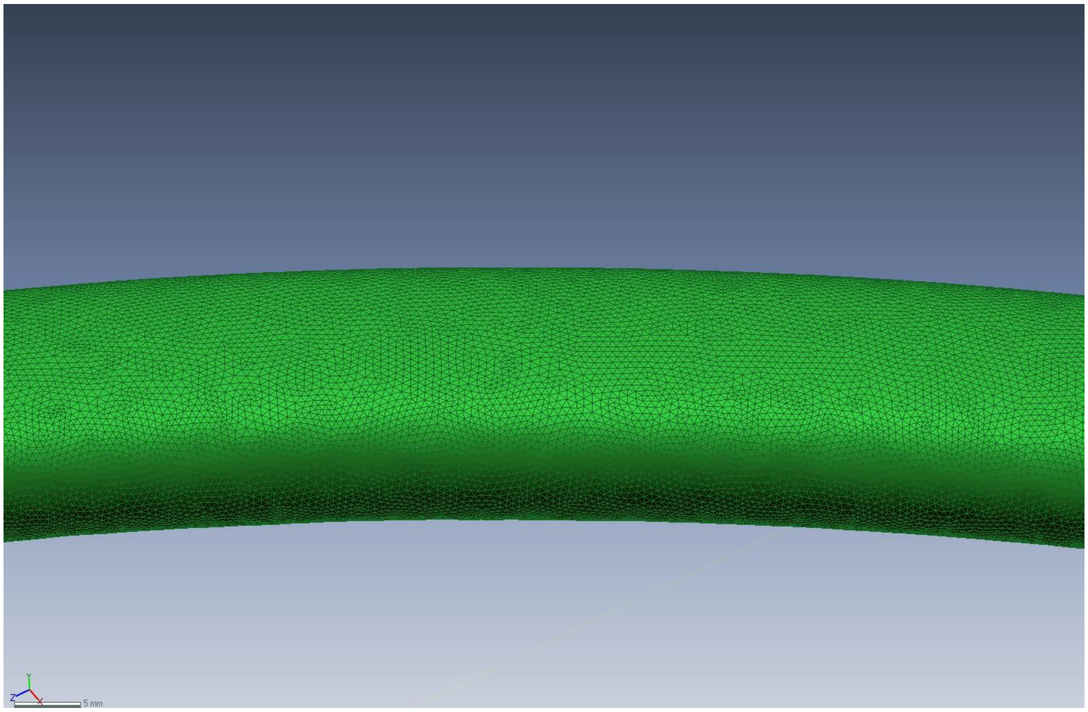


Figure 22. Close-up view of rear frame grip mesh triangulation.

Due to inaccuracies that occur while scanning, the points can be slightly out of place. This results in the mesh having bumps and not being smooth. Several tools can be used within Geomagic to help create a smoother mesh, which makes it easier to generate the surface later. Figure 23 shows the transformation of the rough mesh to the smooth mesh. Also, any unnecessary features of the part were removed using the defeature tool.

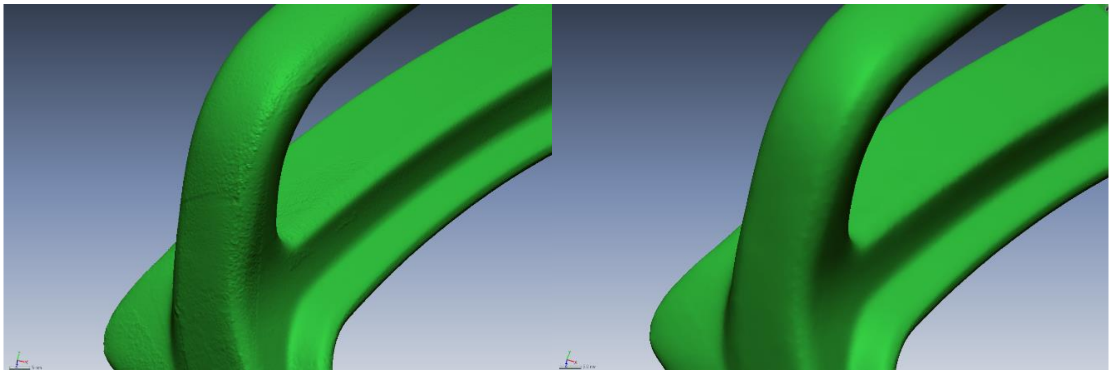


Figure 23. Transformation of rough mesh (left) to smooth mesh (right).

The final step is to generate a surface from the mesh. In order to create a surface from a mesh in Geomagic, the part needs to be broken up into small sections using splines. Surfaces are then generated for each subsection, which when combined forms an overall surface for the entire part. Figure 24 shows the mesh with splines and the resulting surface.

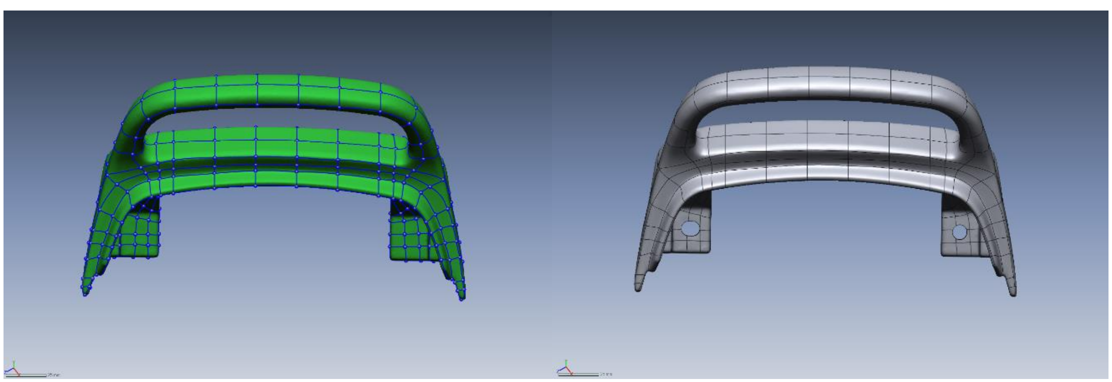


Figure 24. Generated rear frame grip surface (right) from mesh with splines (left).

To summarize the scanning and surface development methodology a flow chart was created (Figure 25). For each part this process was followed to develop surfaces and solid computer models.

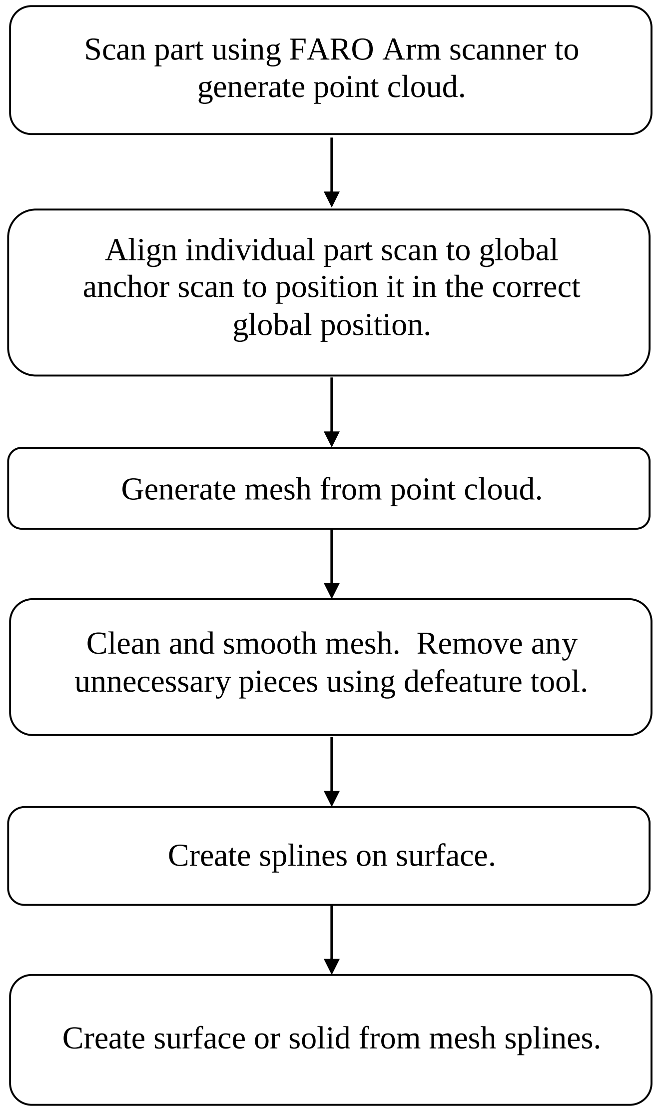


Figure 25. Flow chart demonstrating methodology to develop computer model surface for motorcycle parts.

The scanning process was completed by disassembling the motorcycle and scanning parts as they were removed. After the part was scanned, the mass of the part was measured and documented. If the part had an overall thickness it was measured and documented. The connections of the part to other parts of the motorcycle were documented as well. Additionally, the material type for the part was also documented.

CHAPTER IV

DEVELOPMENT OF FINITE ELEMENT MODEL

IV.1 Part Meshing

The finite element (FE) model of the motorcycle was developed by creating an FE mesh for each part through a software HyperMesh. This FE mesh breaks down the part into small elements that make up the geometry of the part. At each element of the part stress, strain, acceleration, and several other parameters can be measured.

To illustrate the FE meshing process, the left side cover will be used as an example. Using meshing tools within HyperMesh an FE mesh can be generated from a CAD surface or solid. Figure 26 shows this process for the left side cover.

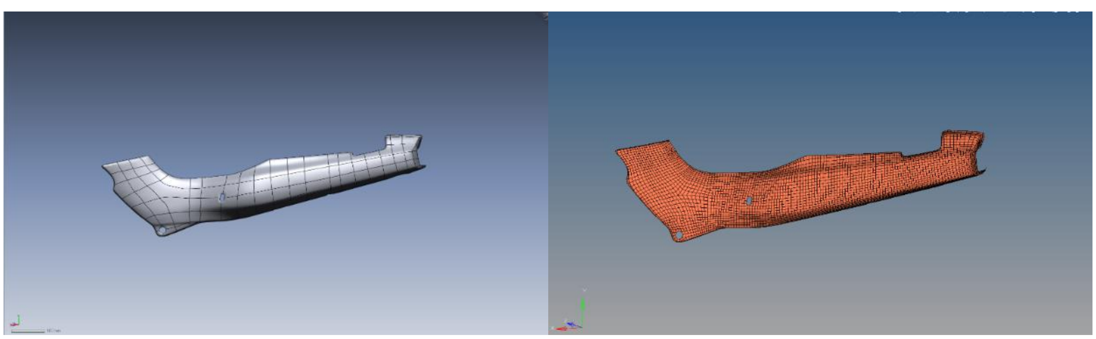


Figure 26. Generation of finite element mesh (right) from surface (left) for left side cover.

This same process was applied for each individual part. The resulting FE mesh model for the entire motorcycle can be seen in Figure 27.

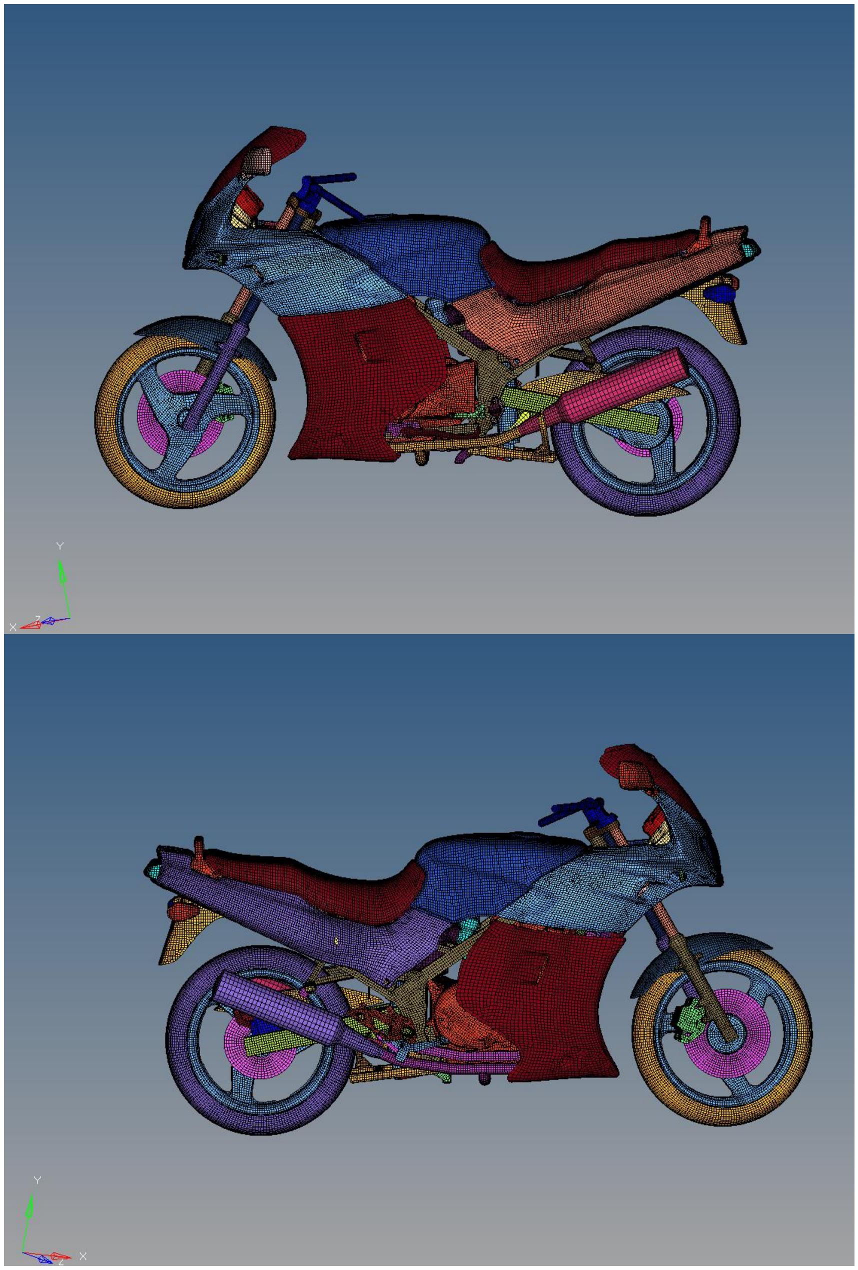


Figure 27. Complete motorcycle FE mesh model side views.

IV.2 Finite Element Model Development

To develop the complete FE model of the motorcycle LS-DYNA, a general purpose finite element program that can perform nonlinear finite element analysis, was used. The meshed parts from HyperMesh were then imported into LS-PrePost, which is a pre- and post-processing software that works with LS-DYNA.

In order to develop a complete motorcycle model the steps and parts of the FE model development are listed below:

- Define connections between parts.
- Develop connection for front axle, rear axle and frame rod.
- Define contact between parts.
- Develop model for tire that includes pressure input.
- Define section properties.
- Define material properties.

The first step was to model the connections between all the parts. A majority of the connections in the motorcycle are simple bolt connections. To model these bolt connections Constrained Nodal Rigid Bodies (CNRBs) were used. CNRBs require specified nodes or points of a part to follow specified nodes or points of another point. This creates a similar constraint that bolt connections provide. Figure 28 shows a simple bolt connection between the left fork and front fender. Figure 29 shows the FE model connection using a CNRB. All bolted connections were modeled similarly for each part based on connection documentation during disassembly.

Figure 28. Motorcycle bolt connection between front left fork and front fender.

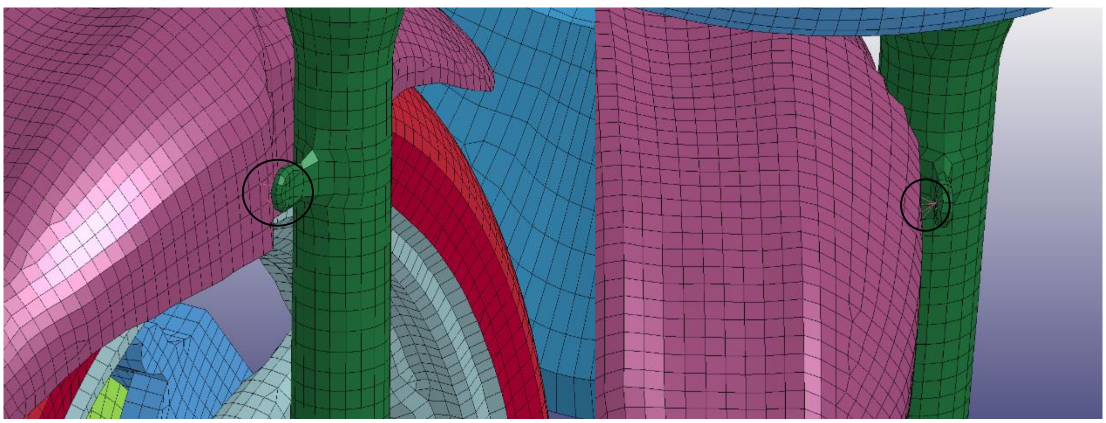


Figure 29. Constrained Nodal Rigid Body Connection in FE model between front left fork and front fender.

The other connections to be modeled are the axles and the connection between the frame and fork holders. In order to model the axles a CONSTRAINED_JOINT_REVOLUTE was defined in the FE model. To define a CONSTRAINED_JOINT_REVOLUTE, two nodes are specified that lie on the axis of rotation, which in this case is the center of the axle rod. These two points are connected by a line as seen in Figure 30 for the front wheel. A set of defined parts are then constrained to rotate around and follow this defined axis of rotation. These parts include the front forks and front wheel for the front axle model. Figure 31 shows the physical axle connection between these parts. This model technique was used for both the front and rear axles.

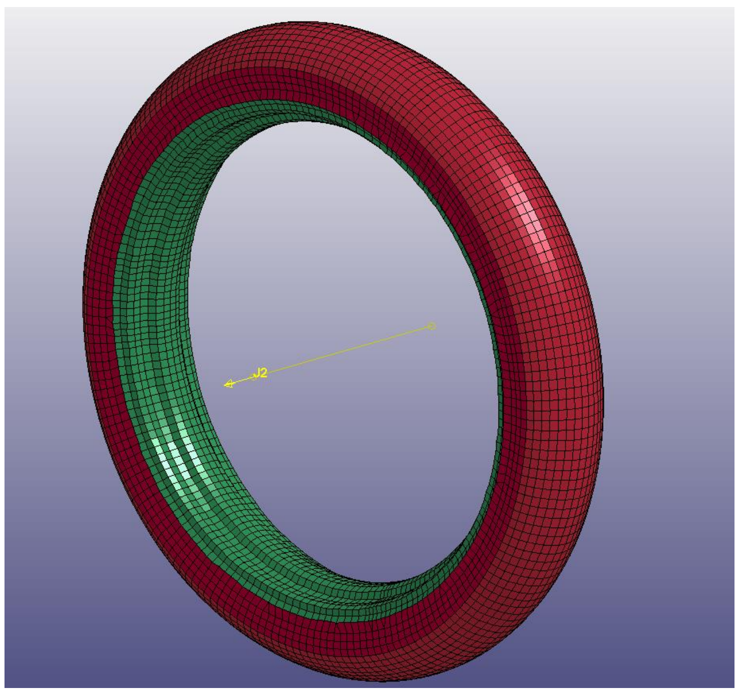


Figure 30. Representation of axle joint for wheel parts to rotate around and follow.

Figure 31. Physical axle joint connection for motorcycle.

Another connection that contains parts rotating around a rod is the connection between the frame and fork holders as seen in Figure 32. The upper and lower fork holders are allowed to rotate around the front cylinder of the frame to allow steering of the motorcycle.

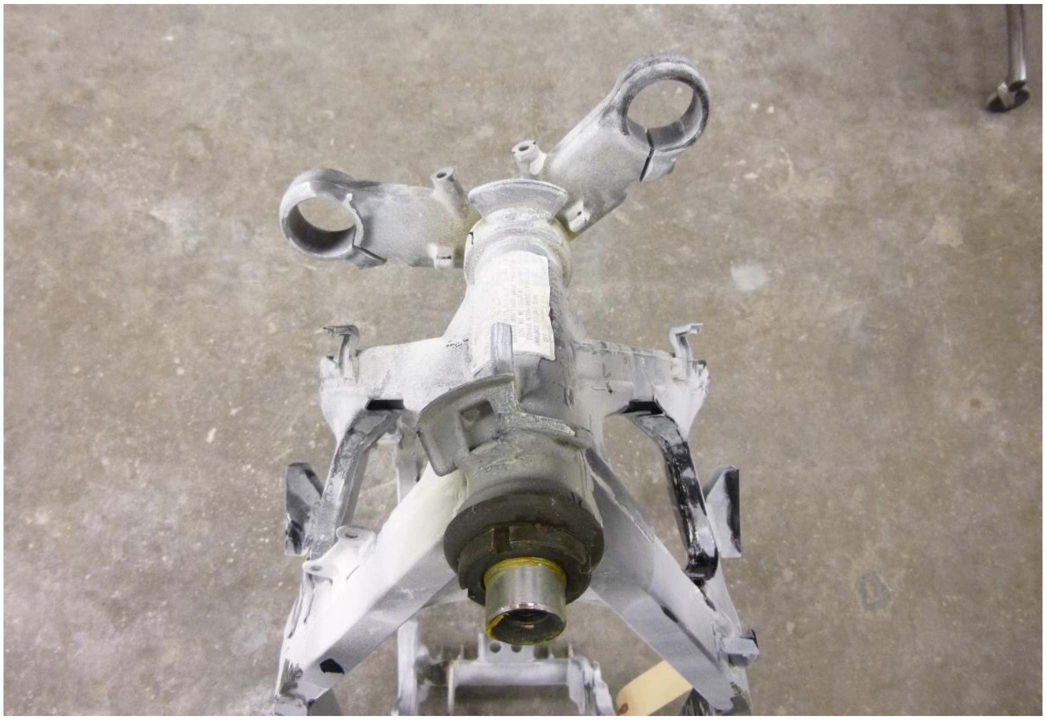


Figure 32. Physical rotating rod that connects to fork holders at front of motorcycle frame.

Similarly to the wheel axles, an axis of rotation was defined by specifying two points that belong on the center of the rotating rod (Figure 33). The frame, upper fork holder, and lower fork holder were all constrained to rotate around and follow this connection.

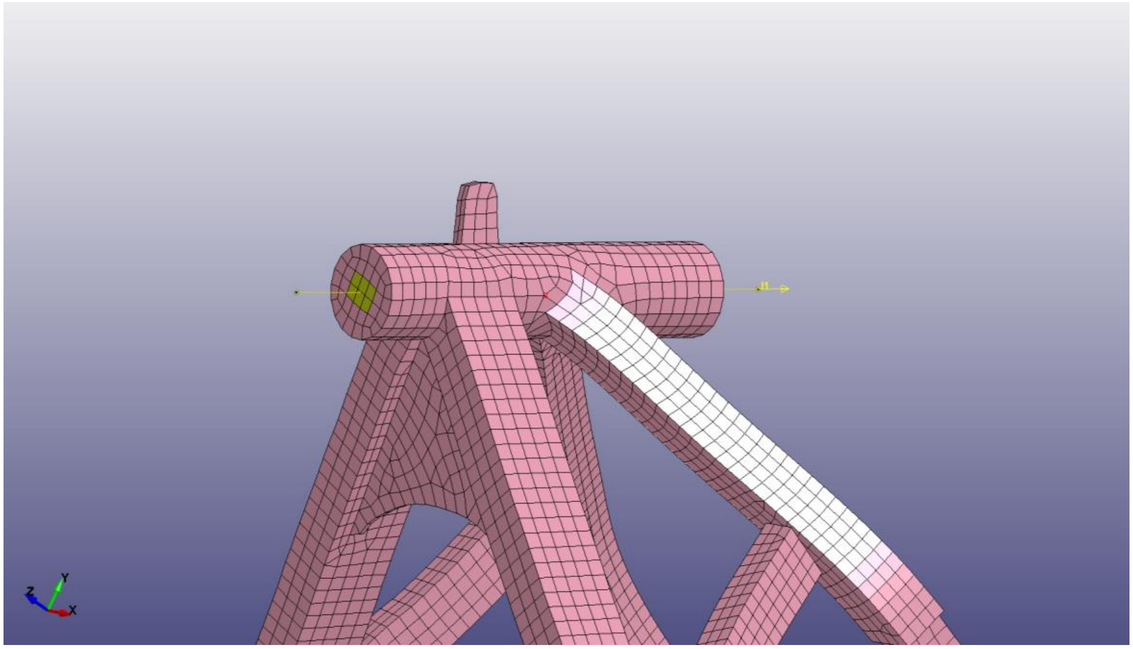


Figure 33. Representation of rotation axis connected to frame and fork holders.

In order to define contact between all the parts in the motorcycle a specific contact type in LS-DYNA was used. In impact simulations a single contact type is commonly used for the vehicle. This contact is referred to as CONTACT_AUTOMATIC_SINGLE_SURFACE. This contact card establishes contact between all the different parts in the motorcycle and even self-part contact.

Another important aspect for the motorcycle FE model are the tire models. Tires have enclosed volumes that contain a specific air pressure. For the Kawasaki Ninja 500R motorcycle the motorcycle tires are specified to have a pressure of 0.28 MPa (41 psi). In order to model this in LS-DYNA, the modeling technique used for airbags can be similarly applied to tires. In LS-DYNA a card

AIRBAG_SIMPLE_PRESSURE_VOLUME is defined, where pressure is defined for a specified volume. The volume is specified by selecting the parts that define the tire volume as seen in Figure 34.

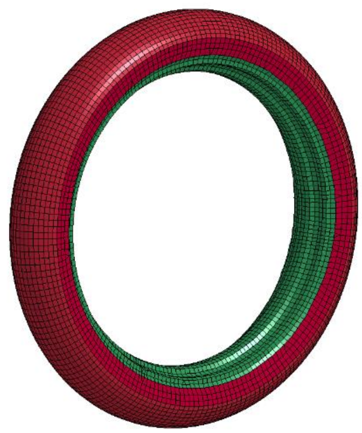


Figure 34. Tire parts that define enclosed volume with specified pressure.

Additionally, it was necessary to define section and material properties for the individual parts of the motorcycle. The elements of individual must have defined section properties, which include necessary inputs such as the thickness of the part and the element formulation. The thicknesses were defined based on documented thickness for parts during disassembly and scanning.

For each part, material properties were assigned to it. During the disassembly of the motorcycle, the material type for each part was documented. All of the materials were categorized into three main material types. This includes steel, plastic, and rubber. The material properties and input parameters for the different material types are summarized in Table 10.

Table 10. Summary of material property inputs.

	E (MPa)	v	Sigy (MPa)	Etan (MPa)
Steel	20,000	0.3	-	-
Plastic	10,000	0.3	20	10
Rubber	300	0.3	-	-

The mass density for each individual part was also specified. These inputs varied for each part based on the measured mass of the part.

The summary of the FE model is provided in Table 11. The average size of the elements was 7.5 mm.

Table 11. Summary of FE model.

Number of Parts	102
Number of Nodes	193170
Number of Elements	194120
Nodal Rigid Body Connections	174
Joint Connections	3

Figures 35 and 36 shows the complete model with mesh and the complete model without mesh compared to the actual motorcycle, respectively.

Figure 35. Complete FE representation of motorcycle with mesh.

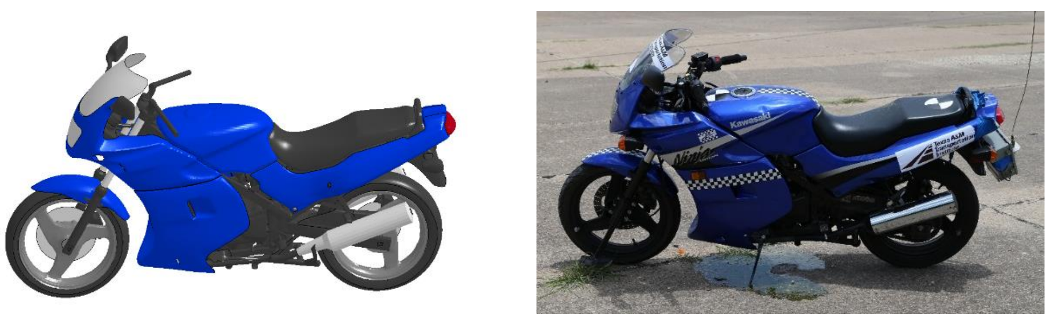


Figure 36. Comparison of FE model without mesh to physical motorcycle.

The total mass for the finite element model is 172 kg (379 lbs), while the mass of the physical motorcycle was 176 kg (388 lbs). To verify the geometrical accuracy of the FE model, several different measurements were taken and compared to the physical specifications of a Kawasaki Ninja 500R motorcycle. Table 12 shows a comparison of the measurements of the physical motorcycle and FE motorcycle. Comparisons of the measurements show that the FE model closely matches that of the physical motorcycle.

The percent difference for each measurement was calculated and all values were below five percent which is reasonable.

Table 12. Comparison of geometrical measurements of physical motorcycle to FE motorcycle.

	Physical Motorcycle (mm)	FE Motorcycle (mm)	Percent Difference (%)
Width	701.0	722.6	3.08
Height	1195.0	1194.0	0.08
Length	2096.0	2094.5	0.07
Wheelbase	1435.0	1448.5	0.94
Wheel Radius	292.1	289.9	0.75
Seat Height	787.4	786.1	0.17
Ground Clearance	150.0	155.0	3.33

CHAPTER V

SIMULATIONS

Several different simulations were conducted to verify the completeness or robustness of the FE model. These initial verification efforts were conducted to ensure element completeness, adequacy of motorcycle part connections, and overall numerical stability of the FE model. The first simulation was conducted by applying a gravity load to the motorcycle. A second simulation was conducted by applying an initial velocity to the motorcycle. These two simulations were successfully performed showing adequate connection details and element completeness.

A third simulation was conducted to ensure overall numerical stability of the computer model. This simulation was performed by impacting the motorcycle head-on into a rigid wall. The motorcycle was given a speed of 48.3 km/h (30 mph), which is based on ISO 13232-7 testing standards. Figures 37 and 38 show the setup of the motorcycle placed just in front of the wall. The simulation was run for 0.04 seconds, which is the time when the motorcycle began to rebound away from the wall. Table 13 shows sequential frames of the simulation of the motorcycle impacting the wall.

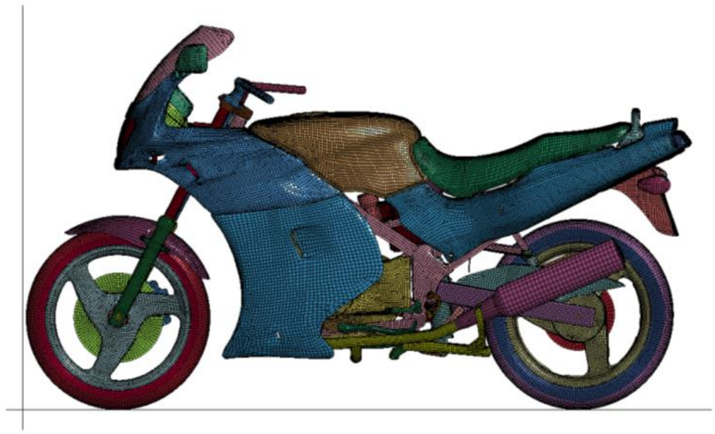


Figure 37. Side view of simulation setup for head-on impact.

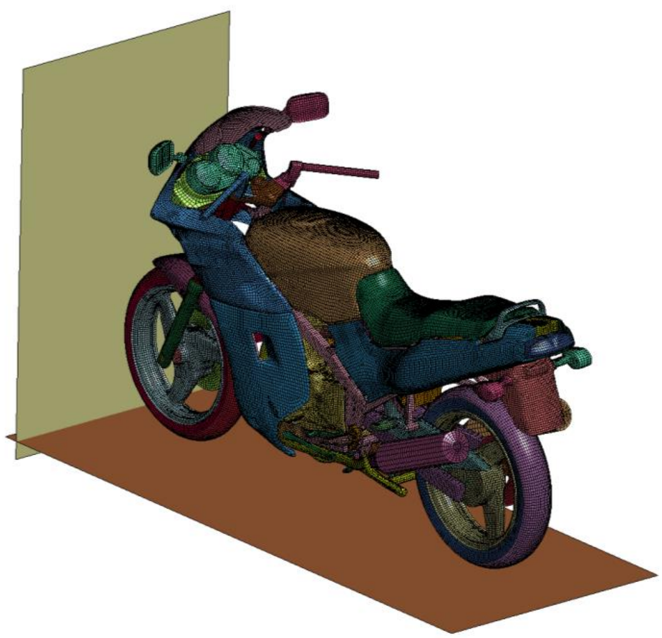
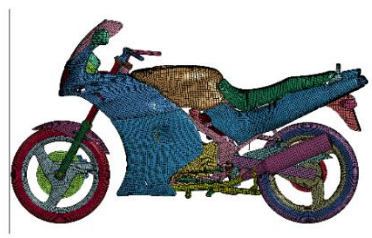
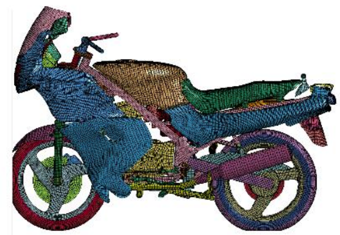
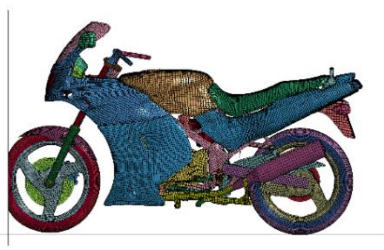
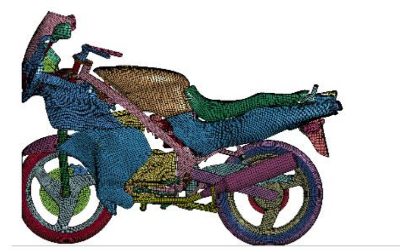
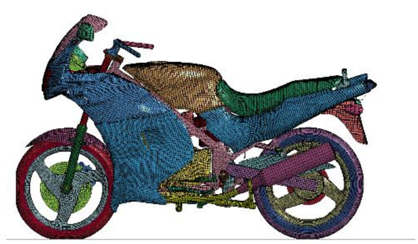
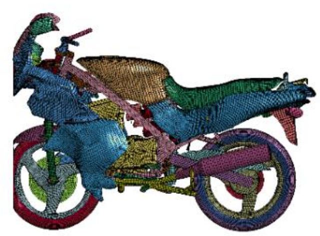
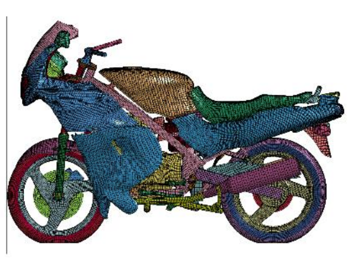
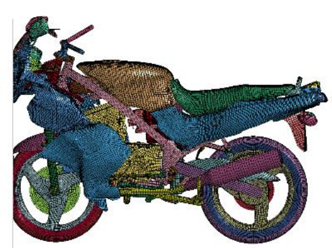


Figure 38. Perspective view of simulation setup for head-on impact.

Table 13. Sequential frames from simulation of motorcycle impacting rigid wall.

Time (s)	Sequential Frames	Time (s)	Sequential Frames
0.000		0.024	
0.006		0.030	
0.012		0.036	
0.018		0.040	

A plot of displacement versus time for a point at the center of the front wheel is shown in Figure 39. The front wheel makes initial contact with the wall and begins to rebound around 0.006 seconds. As the wheel begins to rebound away from the wall the rest of the motorcycle contacts the front wheel and pushes it back toward the wall. At 0.0175 seconds the wheel makes contact with the wall again along with the rest of the motorcycle. The entire motorcycle begins to rebound away from the wall at 0.04 seconds.

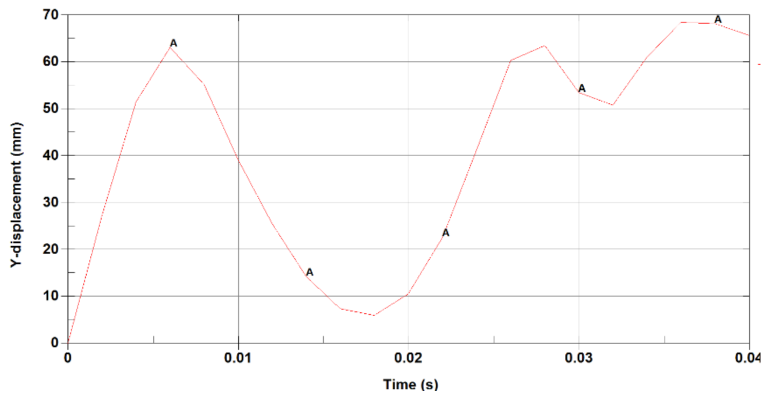


Figure 39. Displacement of center of front wheel.

To ensure numerical stability a few different checks on energy and mass were made for the resulting simulation. Table 14 shows the evaluation criteria and checks performed.

Table 14. Evaluation criteria for numerical stability and model robustness.

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	8.7	YES
Hourglass Energy of the analysis solution at the end of the run is less than five percent of the total initial energy at the beginning of the run.	0.13	YES
The part/material with the highest amount of hourglass energy at any time during the run is less than five percent of the total initial energy at the beginning of the run.	0.015	YES
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0.24	YES
The part/material with the most mass added had less than 10 percent of its initial mass added.	4.3	YES
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	0	YES
There are no shooting nodes in the solution?	No	YES
There are no solid elements with negative volumes?	No	YES

The resulting energies from the simulation were plotted as seen in Figure 40. This includes total, kinetic, internal, hourglass, and sliding interface energy.

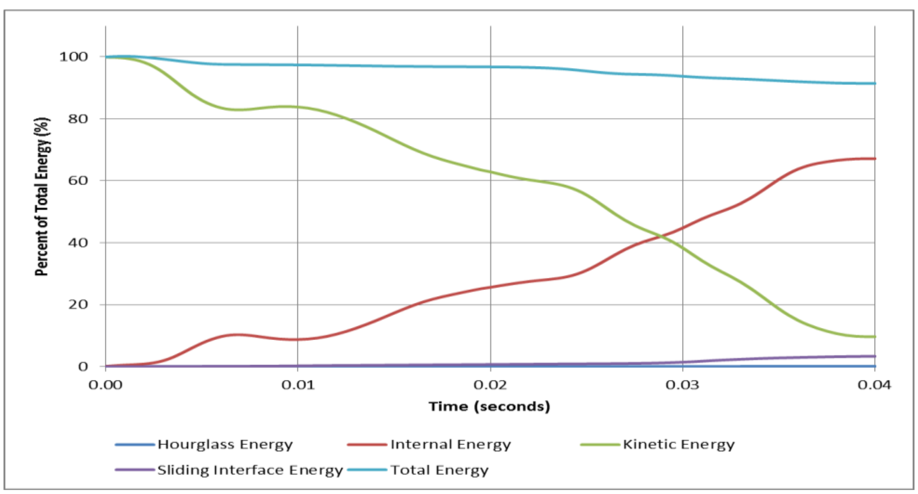


Figure 40. Energy plot summary for simulation.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

A finite element model of a Kawasaki Ninja 500R motorcycle was successfully developed through reverse engineering techniques. The FE motorcycle model consisted of 194,120 elements and included all structural parts of the motorcycle. Non-structural parts such as electric wiring, brake line, gear chain, etc. were not included in the model.

The finite element model was validated for geometrical accuracy and initial robustness. The geometrical validation efforts were conducted by comparing physical measurements of the motorcycle to that of the FE model. Three different simulations were conducted to verify initial robustness of the model. This included a simulation with applied gravity, a simulation with applied velocity, and a simulation with the motorcycle impacting a rigid wall with a speed of 48.3 km/h (30 mph). Each simulation produced acceptable results and showed no numerical instability throughout the simulation.

Efforts still remain to continue to validate the accuracy of the FE model. While the current FE model has been validated for initial robustness, additional work remains to validate motorcycle response behavior for significant components (i.e. suspension system, fuel tank, steering, etc.) and overall motorcycle response in a physical crash test. The identification of material properties can be performed through coupon testing or non-destructive testing.

The development of this FE model can provide researchers with a variety of applications. Motorcycle crashes can occur in a number of different ways and scenarios. Being able to re-produce these different scenarios through simulations instead of physical crash tests saves significant time and money.

REFERENCES

AASHTO "Manual for Assessing Safety Hardware," American Association of State Highway and Transportation Officials, Washington, D.C., USA, 2009.

AENOR "Standard UNE 135900-1," 2005.

AENOR "Standard UNE 135900-1," 2008.

Barbani, D., M. Pierini and N. Baldanzini, "FE Modelling of a Motorcycle Tyre for Full-Scale Crash Simulation," International Journal of Crashworthiness, 2012.

Bhosale, P. V., "Exploratory Study on the Suitability of an Airbag for an Indian Motorcycle Using Finite Element Computer Simulations of Rigid Wall Barrier Tests," Proceedings of the 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV), 2013.

Bothwell, P.W. and H.C. Petersen, "Dynamics of Motorcycle Impact, Vol. I," DOT HS 800 586, 1971.

Bothwell, P.W., R.E. Knight, and H.C. Petersen, "Dynamics of Motorcycle Impact, 1971-1973, Vol. I" DOT HS 800 906, 1973.

Canaple, B., G. P. Rungen, E. Markiewicz, P. Drazetic, J. Happian-Smith, B. P. Chinn, and D. Cesari, "Impact Model Development for the Reconstruction of Current Motorcycle Accidents," International Journal of Crashworthiness, 2002.

Chawla, A. and S. Mukherjee, "Motorcycle Safety Device Investigation: A Case Study on Airbags," Sadhana, Vol. 32, No. 4, 427-443, 2007.

Chawla, A., S. Mukherjee, D. Mohan, M. Singh, M. Sakurai, and T. Nakatani, "A Methodology for Car-Motorcycle Crash Simulation," JARI Research Journal, 2001.

Chawla, A., S. Mukherjee, D. Mohan, D. Bose, and P. Rawat, "FE Simulations of Motorcycle-Car Frontal Crashes, Validation and Observations," Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 2003.

Chinn, B.P. and P.D. Hope, "Protecting Motorcyclists' Legs," Proceedings of the 11th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 1987.

Chinn, B.P., J. Happian-Smith and M.A. Macaulay, "The Effect of Leg Protecting Fairings on the Overall Motion of a Motorcycle in a Glancing Impact," International Journal of Impact Engineering, 1989.

Chinn, B.P., J. A. Okello, P. J. McDonough, and G. Grose, "Development and Testing of a Purpose Built Motorcycle Airbag Restraint System," Proceedings of the 15^{th} International Technical Conference on the Enhanced Safety of Vehicles (ESV), 1996.

Deguchi, M., "Modelling of a Motorcycle for Collision Simulation," Proceedings of the 18^{th} International Technical Conference on the Enhanced Safety of Vehicles (ESV), 2003.

Duncan C., B. Corben, N. Truedsson, and C. Tingvall, "Motorcycle and Safety Barrier Crash-Testing: Feasibility Study," Report, Accident Research Centre, Monash University, Australia, 2000.

EN1317-2 "Road Restraint Systems - Part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers including vehicle parapets," European Standard, European Committee for Standardization, Brussels, Belgium, 2010.

EN1317-8 "Road Restraint Systems - Part 8: Motorcycle Road Restraint Systems which Reduce the Impact Severity of Motorcyclist Collisions with Safety Barriers," European Committee for Standardization, Brussels, Belgium, 2011.

FEMA "The Road to Success - Improving Motorcyclists' Safety by Improving Crash Barriers," Federation of European Motorcyclist's Associations, 2005.

FEMA "Final report of the Motorcyclists & Crash Barriers Project," Federation of European Motorcyclist's Associations, 2010.

Happian-Smith, J., M.A. Macaulay and B.P. Chinn, "Motorcycle Impact Simulation and Practical Verification," Proceedings of the 11^{th} International Technical Conference on the Enhanced Safety of Vehicles (ESV), 1987.

Happian-Smith, J. and B.P. Chinn, "Simulation of Airbag Restraint Systems in Forward Impacts of Motorcycles," No. 900752 SAE Technical Paper, 1990.

Ibitoye, A. B., A. M. Hamouda, S. V. Wong and R. S. Umar, "Simulation of Motorcycle Crashes with W-Beam Guardrail: Injury Patterns and Analysis," Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 2009.

Iijima, S., S. Hosono, A. Ota, and T. Yamamoto, "Exploratory Study of an Airbag Concept for a Large Touring Motorcycle," Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 1998.

ISO 13232 "Motorcycles-Test and Analysis Procedures for Research Evaluation of Rider Crash Protection Devices Fitted to Motorcycles," ISO 13232, International Organization for Standardization, Geneva, Switzerland, 2005.

Kebschull, S.K., J. W. Zellner, M. V. Auken, and N. M. Rogers, "Injury Risk/Benefit Analysis of Motorcyclist Protective Devices Using Computer Simulation and ISO 13232," Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 1998.

Knight, R.E. and H.C. Petersen, "Dynamics of Motorcycle Impact, Vol III," DOT HS 800 588 1971.

Knight, R.E. and H.C. Petersen, "Dynamics of Motorcycle Impact, Vol III," DOT HS 800 908 1973.

Knight, R.E. and H.C. Petersen, "Dynamics of Motorcycle Impact III," Denver Research Inst., 1976.

Kuroe, T., S. Iijima and H. Namiki, "Exploratory Study of an Airbag Concept for a Large Touring Motorcycle: Further Research Second Report," Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 2005.

L.I.E.R. "Protocol: Motorcyclist Safety Evaluation Regarding Safety Barriers," 1998.

Mukherjee, S., A. Chawla, D. Mohan, M. Singh, M. Sakurai, and T. Nakatani, "Motorcycle-Wall Crash: Simulation and Validation," PAM-CRASH Users Conference Assembly, 2001.

Mukherjee, S., A. Chawla, D. Mohan, M. Singh, M. Sakurai, and Y. Tamura, "Motorcycle-Car Side Impact Simulation," Proc. IRCOBI, 2001.

Nakatani, T., M. Sakurai, A. Chawla, and S. Mukherjee, "A Methodology for Motorcycle-vehicle Crash Simulation – Development of Motorcycle Computer Simulation Model," JARI Research Journal, 2001.

Namiki, H., T. Nakamura, and S. Iijima, "A Computer Simulation for Motorcycle Rider-Motion in Collision," No. 2003-32-0044, SAE Technical Paper, 2003.

Namiki, H., T. Nakamura, and S. Iijima, "A Computer Simulation for Motorcycle Rider Injury Evaluation in Collision," Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 2005.

Nieboer, J.J., J. Wismans, C. M. Versmissen, M. T. P van Slagmaat, I. Kurawaki, and N. Ohara, "Motorcycle Crash Test Modelling," No. 933133, SAE Technical Paper, 1993.

Page M. and J. Bloch, "Evaluation Procedures of Motorcyclist Protection Devices," Europeanroads Review, ERR 16, 16th IRF World Meeting Sharing the Road, 2010.

Ramamurthy, S., "Kinematic Analysis of a Motorcycle and Rider Impact on a Concrete Barrier Under Different Impact and Road Conditions," Master Thesis, Wichita State University, 2007.

Rogers, N.M., "Evaluation of TRL Designed Leg Protectors for a Medium Sized Sport Motorcycle," Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 1994.

Rogers N.M. and J.W. Zellner, "An Overall Evaluation of UKDS Motorcyclist Leg Protectors Based on ISO 13232," Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 1998.

Rogers, N.M., J. W. Zellner, A. Chawla and T. Nakatani, "Methodologies for Motorcyclist Injury Prediction by Means of Computer Simulation," Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 2005.

Wang, Y. and M. Sakurai, "Development and Verification of a Computer Simulation Model of Motorcycle-to-Vehicle Collisions," No. 1999-01-0719, SAE Technical Paper, 1999.

Yettram, A.L., J. Happian-Smith, M. A. Macauley, and B. P. Chinn, "Computer Simulation of Motorcycle Crash Tests," Proceedings of the 14th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 1994.

Zellner, J.W., J.A. Newman, and M. Nicholas, "Preliminary Research into the Feasibility of Motorcycle Airbag Systems," Proceedings of the 14th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 1994.

Zellner J.W., K.D. Wiley, N.L. Broen, and J.A. Newman, "A Standardized Motorcyclist Impact Dummy for Protective Device Research," Proceedings of the 15th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 1996.